Ligand Effects

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Molecular Dynamics and Ligand Exchange in Magnesium Complexes: Evidence for both Dissociative and Associative Ligand Exchange**

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Dedicated to Sir John Meurig Thomas FRS on the occasion of his 80th birthday

The chemistry of Grignard reagents is among of the most mature in organometallic chemistry, and it continues to inspire interest and reveal new results as seen in the development of turbo-Grignard reagents and the alkali-metal activation of C–H bonds by the Strathclyde school of s-block element chemistry.[1–7] The reactivity of the magnesium alkyl group has long been known to be highly solvent dependent as, indeed, is found for organolithium and organozinc reagents.[8–12] In part this arises from the kinetic lability of these ions and the extensive equilibria, typified by the so-called Schlenk equilibrium, present in polar coordinating solvents.[13] We recently reported the synthesis of a series of magnesium alkyls of the form [LMgR(thf)] where L represents one of the chelating anionic ligands shown in **A** and **B**.[14] The molecular structure of the β-diiminato-supported *n*-butyl complex is also shown (Figure 1).

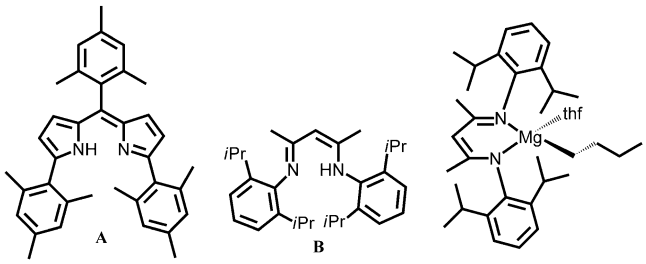

Figure 1. Representations of the chelating pyrromethene and β-diiminate ligands and the molecular structure of [LMg*n*Bu(thf)].

The purpose of this earlier study was aimed at the taming of the kinetically labile Mg^{2+} center and the suppression of the Schlenk equilibrium with the ultimate hope of developing the chemistry of the MgR moiety within a well-defined pocket and coordination environment. During this study the ring-opening polymerization (ROP) of lactide was studied employing the *n*-butylmagnesium complexes as initiators. The initiation step involved β-hydrogen-atom transfer with the formation of the ring-opened lactide bound to the Mg center as an alkoxide and the elimination of 1-butene.[14] During the subsequent enchainment of *rac*-lactide it was noted that while atactic polylactide (PLA) was formed in the noncoordinating solvents, toluene and dichloromethane, the addition of THF favored the formation of heterotactic PLA with isi/sis tetrads. Indeed, in neat THF solution, the P_r value for isi/sis tetrads was greater than 95%, which implicated the presence of THF during the ring-opening event. Earlier work had also noted the influence of THF on the stereo-outcomes in the ROP of *rac*-LA, and while structures of complexes determined by single-crystal X-ray crystallography are insightful with respect to ground-state and thermally persistent species they are of less relevance in mechanistic considerations of reactivity. Consequently, we examined the mechanism of ligand exchange in complexes of the form [LMg*n*Bu(L′)] where L is one of the chelating anionic ligands shown in **B** and L′ is thf, 2-methyltetrahydrofuran (2-MeTHF), pyridine (py), and 4-dimethylaminopyridine (DMAP). We report herein a summary of results as determined from variable-temperature NMR spectroscopy.

The title complexes were prepared by the addition of the donor ligand L′ (L′ = thf, 2-MeTHF, py, or DMAP) to the hexane-soluble product formed in the reaction between LH and Mg*n*Bu_2. The preparation and structure of the thf complexes[14] have been previously described as has that of the pyridine adduct.[15]

The molecular structures of [LMg*n*Bu(thf)] and [LMg*n*Bu(py)] can be described as pseudotetrahedral coordination about Mg^{2+} where the pyridine or thf is bound more weakly, as evidenced by its longer Mg–N or Mg–O bond distances. That is to say, the structure is distorted toward the trigonal-planar geometry involving the unsolvated [LMg*n*Bu] molecular fragment.[14,15]

The exchange between the thf-containing complex and free THF has been studied in [D_8]toluene and CD_2Cl_2 by both ^1H and $^{13}C\{^1H\}$ NMR spectroscopy in the temperature range between −100 °C and 100 °C ([D_8]toluene). The added concentrations of THF have been from 0.2 to 2.5 equivalents and the rates of exchange have been simulated by a detailed line-shape analysis. Experimental and simulated $^{13}C\{^1H\}$ NMR spectra are shown in Figure 2 and kinetic data are given in Table 1.

The key finding from this work is that the exchange process is dissociative as shown in Scheme 1. For the dissociative THF exchange we calculate $\Delta H^{\ddagger} = (13.4 \pm 0.4)$ kcal mol^{-1} and $\Delta S^{\ddagger} = (+6.3 \pm 1.6)$ cal mol^{-1} K^{-1}.

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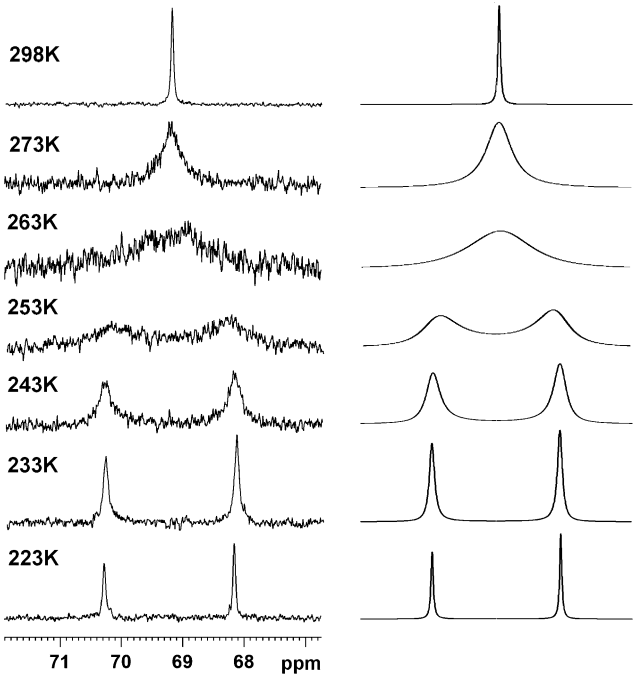
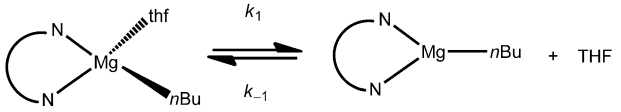


Figure 2. Variable-temperature ^{13}C NMR (125 MHz) spectra of 0.035 M [LMg*n*Bu(thf)] with 0.038 M THF (1:1.09) in [D_8]toluene. Both the experimental (left) and simulation (right) data are shown only for the α-carbon atoms of thf. The signal(1) for the coordinated thf is downfield of that for the free THF.

Table 1: The values of $1/(\tau_{LMgnBu(THF)})$ (k_1) from ^{13}C NMR line-shape analysis simulation at 0.035 M of [LMg*n*Bu(THF)] and different added THF concentrations and temperatures.[a]

Equiv. added THF	Free THF	$1/(\tau_{LMgnBu(THF)}) = k_1$ 223 K	233 K	243 K	253 K	263 K	273 K	300 K
0.20	0.0070	10	33	100	280	950	2000	35 000
0.23	0.0080	10	33	100	280	950	2000	35 000
0.32	0.0112	10	33	100	280	950	2000	35 000
0.66	0.0232	10	33	100	280	950	2000	35 000
0.78	0.0273	10	33	100	280	950	2000	35 000
1.09	0.0382	10	33	100	280	950	2000	35 000
1.21	0.0422	10	33	100	280	950	2000	35 000
1.50	0.0525	10	33	100	280	950	2000	35 000
2.00	0.0700	10	33	100	280	950	2000	35 000
2.36	0.0826	10	33	100	280	950	2000	35 000

[a] See the Experimental Section and Supporting Information for details.



Scheme 1. The dissociative process of the [LMg*n*Bu(thf)] complex.

We have also similarly examined the ligand exchange process involving 2-MeTHF and pyridine. The exchange involving 2-MeTHF occurs more readily while that involving pyridine self-exchange is slower. The related complex involving L′ = DMAP has an even slower exchange with added DMAP. Thus, the exchange reflects the Mg-L′ bond strengths which are in the order of DMAP > py > thf > 2-MeTHF. Interestingly, the rates of aryl group rotation, which can be monitored by both ^1H and $^{13}C\{^1H\}$ NMR spectroscopy, reveal within experimental error the identical activation energies when compared to the L′ dissociative process. The aryl group rotation involves exchange of equal site populations and is readily monitored by following the methine CH signals of the 2,6-diisopropylphenyl ligands of the β-diiminate (L). The coalescence temperatures for aryl group rotation in [D_8]toluene at 500 MHz are: −40 °C (2-MeTHF), −15 °C (thf), 35 °C (py), and 75 °C (DMAP; Figure 3). Given the

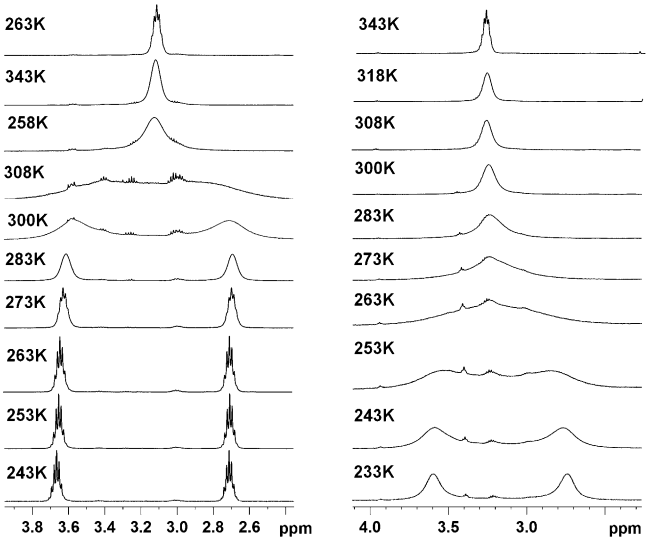
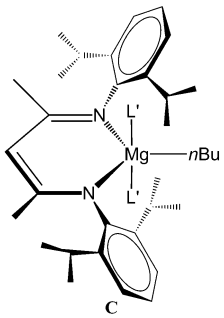


Figure 3. Variable-temperature ^1H NMR spectra of C*H*Me_2 of the aryl ring of [LMg*n*Bu(py)] (0.035 M) in [D_8]toluene (left) and [D_5]py (right).

steric crowding at the four-coordinate metal centers in the [LMg*n*Bu(L′)] complexes, it is not surprising that aryl group rotation is restricted. Upon dissociation of L′ one anticipates a three-coordinate Mg^{2+} ion akin to that of the [LZn*n*Bu] which has little affinity to bind Lewis bases. The crystal structures of similar three-coordinate zinc alkyl analogues were previously reported by Parkin and co-workers in 2010.[16] Indeed, this zinc compound, [LZn*n*Bu], shows extremely facile aryl group rotation which cannot be frozen out on the NMR time scale, even at −100 °C in [D_8]toluene. We should note that Mg^{2+} and Zn^{2+} have essentially identical ionic radii, and thus steric constraints on the rotation of the aryl ligands of the β-diiminate should be similar.[17]

Interestingly, the coalescence behavior of the aryl group rotation is temperature dependent in the presence of a relatively large excesses of L′ in [D_8]toluene. Thus, a limiting coalescence is obtained when the solvent employed is [D_8]THF or [D_5]pyridine for the complexes [LMg*n*Bu(L′)] where L′ is thf or py, respectively. Here we observed in neat [D_8]THF that the coalescence temperature is suppressed from −15 °C to −75 °C, and for the pyridine complex in [D_5]pyridine from 35 °C to −15 °C. This suppression is quite a dramatic and systematic change in the rate of aryl group rotation for each complex and leads us to suggest that in the

presence of a significant excess of the L′ the complex is capable of showing an exchange process involving L′ by an interchange associative mechanism. It is easy to envisage a five-coordinate interchange activated complex where the Mg^{2+} ion is in a pseudo-trigonal-bipyramidal geometry as shown **C**. Here the aryl isopropyl ligands become equivalent. We note the recent report by Mountford and co-workers that the complex [LMg-(BH_4)(thf)] has similar restricted rotation of the aryl groups whereas the bis(thf) complex of calcium [LCa-$(BH_4)(thf)_2$] shows equivalent isopropyl groups.[18]



C

If we assume that the activation parameters for the aryl group rotation in neat [D_8]THF correlate with the dissociative plus associative interchange processes, we can obtain the activation parameters for the associative interchange as $\Delta H^{\neq} = (5.4 \pm 0.1)$ kcal mol^{-1} and $\Delta S^{\neq} = (-20.9 \pm 0.3)$ cal mol^{-1} K^{-1}.

The above findings are particularly relevant to the reactions involving [LMg*n*Bu(thf)] and *rac*-lactide (LA). In toluene and dichloromethane these reactions are extremely fast but show no stereoselectivity, whereas in THF, the reactions, though still rapid, are relatively slower and show a high propensity for the formation of heterotactic PLA. In the presence of excess THF, the LA monomer presumably has to react by an associative process where THF is still present within the coordination sphere of the metal center. While this conclusion has been inferred previously,[14] the present study provides more substantial evidence that this kinetically labile Mg^{2+} ion can react through both a dissociative and an associative interchange mechanism.

Experimental Section

NMR Spectroscopy. Variable-temperature ^{1}H and ^{13}C NMR spectra were acquired on a Bruker DPX-500 NMR Spectrometer from 183 to 363 K, using a J-young NMR tube. The temperature of the probe was adjusted with a standard temperature-control unit, using liquid nitrogen at low temperature and a heating element at high temperature. The probe temperature was calibrated by using methanol standard for low temperature and 80% ethylene glycol in DMSO standard for high temperature. The accuracy of the temperature measurement was (±0.5)°C.[19,20] The probe was tuned at each temperature and the sample tubes were left in the probe for at least 15 min to achieve the thermal equilibrium before taking measurements. The spectra were referenced by the residual priority impurity of [D_8]toluene at 2.08 ppm (^{1}H NMR) and 137.86 ppm (^{13}C NMR), [D_8]THF at 3.58 ppm (^{1}H NMR) and 67.57 ppm (^{13}C NMR), [D_5]py at 8.74 ppm (^{1}H NMR) and 150.35 ppm (^{13}C NMR).

Chemicals and Solutions. Deuterated toluene, THF, and pyridine were purchased from Cambridge Isotope Laboratory, stirred over calcium hydride overnight, distillated under nitrogen gas, and stored over 4 Å molecular sieves overnight prior use. The solutions were made inside glove-box under nitrogen atmosphere and transferred to a J-young NMR tube.

Line-shape Analyses. The programs were written based on the density formulism developed by Fraenkel and Kaplan.[21] The density-matrix equations used for ^{13}C NMR spectrum simulations of different temperatures is based on the two uncoupled site exchange system and they are derived with and without explicit exchanging mechanism. All the information is provided in supporting information.

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[1] R. E. Mulvey, *Acc. Chem. Res.* **2009**, *42*, 743 – 755.
[2] A. Krasovskiy, P. Knochel, *Angew. Chem.* **2004**, *116*, 3396 – 3399; *Angew. Chem. Int. Ed.* **2004**, *43*, 3333 – 3336.
[3] R. Campbell, D. Cannon, P. García-Álvarez, A. R. Kennedy, R. E. Mulvey, S. D. Robertson, J. Saßmannshausen, T. Tuttle, *J. Am. Chem. Soc.* **2011**, *133*, 13706 – 13717.
[4] A. E. Jensen, W. Dohle, I. Sapountzis, D. M. Lindsay, V. A. Vu, P. Knochel, *Synthesis* **2002**, 565 – 569.
[5] See Ref. [4].
[6] H. Ren, A. Krasovskiy, P. Knochel, *Chem. Commun.* **2005**, 543.
[7] L. Boymond, M. Rottländer, G. Cahiez, P. Knochel, *Angew. Chem.* **1998**, *110*, 1801 – 1803; *Angew. Chem. Int. Ed.* **1998**, *37*, 1701 – 1703.
[8] S. H. Wiedemann, A. Ramírez, D. B. Collum, *J. Am. Chem. Soc.* **2003**, *125*, 15893 – 15901.
[9] X. Sun, D. B. Collum, *J. Am. Chem. Soc.* **2000**, *122*, 2459 – 2463.
[10] X. Sun, D. B. Collum, *J. Am. Chem. Soc.* **2000**, *122*, 2452 – 2458.
[11] P. Knochel, R. D. Singer, *Chem. Rev.* **1993**, *93*, 2117 – 2188.
[12] E. Erdik, Ö. Ö. Pekel, *J. Organomet. Chem.* **2008**, *693*, 338 – 342.
[13] W. Schlenk, W. J. Schlenk, *Ber. Dtsch. Chem. Ges. B* **1929**, *62*, 920 – 924.
[14] M. H. Chisholm, K. Choojun, J. C. Gallucci, P. M. Wambua, *Chem. Sci.* **2012**, *3*, 3445 – 3457.
[15] M. S. Hill, D. J. MacDougall, M. F. Mahon, *Dalton Trans.* **2010**, *39*, 11129 – 11131.
[16] K. Pang, Y. Rong, G. Parkin, *Polyhedron* **2010**, *29*, 1881 – 1890.
[17] R. D. Shannon, *Acta Crystallogr. Sect. A* **1976**, *32*, 751 – 767.
[18] R. A. Collins, J. Unruangsri, P. Mountford, *Dalton Trans.* **2012**, *42*, 759 – 769.
[19] A. L. Van Geet, *Anal. Chem.* **1970**, *42*, 679 – 680.
[20] D. S. Raiford, C. L. Fisk, E. D. Becker, *Anal. Chem.* **1979**, *51*, 2050 – 2051.
[21] J. I. Kaplan, G. Fraenkel, *NMR of Chemically Exchanging Systems*, Academic Press, New York, **1980**.

