

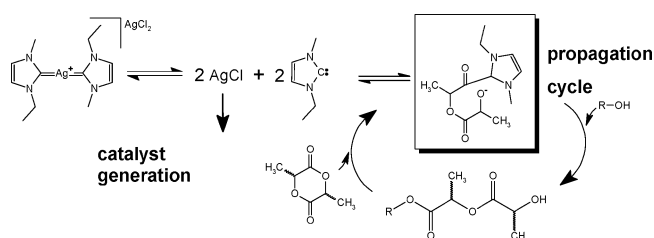
Silver(I)–Carbene Complexes/Ionic Liquids: Novel *N*-Heterocyclic Carbene Delivery Agents for Organocatalytic Transformations

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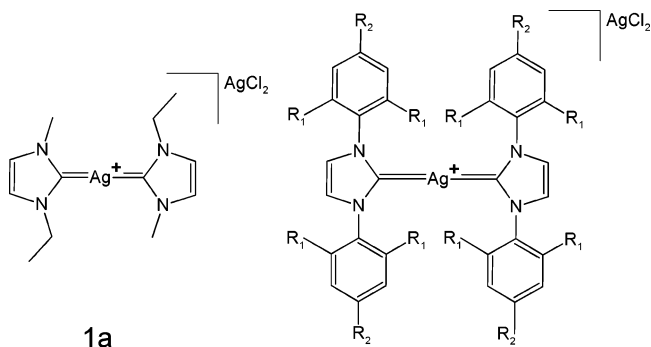


*N*-Heterocyclic carbene (NHC) complexes with silver were investigated as sources of unsaturated NHC carbene catalysts via thermal decomposition. The NHC complex (1-ethyl-3-methylimidazol-2-ylidene)silver(I) chloride is an ionic liquid, and was found to catalyze the ring-opening polymerization of lactide at elevated temperatures to give narrowly dispersed polylactide of predictable molecular weight. Silver–carbene complexes can also be used for the catalysis of small molecule transesterification reactions. Thermolysis of the silver complexes in the presence of CS<sub>2</sub> yielded the zwitterionic CS<sub>2</sub> adducts of the carbene, implicating the intermediacy of the free carbene in these reactions.

Stable *N*-heterocyclic carbenes (NHCs) have been a significant area of study since their description by Wanzlick<sup>1</sup> and Arduengo.<sup>2</sup> These compounds have found use as ligands for transition metal catalysts,<sup>3</sup> and as nucleophilic catalysts for various organic transformations.<sup>4–6</sup> However, these carbenes are sensitive to air and moisture, which can make the isolation and use of these compounds difficult. It has been recently demonstrated that carbenes can be generated in situ from *tert*-butoxide

and imidazolium and imidazolinium salts and used directly as transesterification catalysts.<sup>5,6</sup> Furthermore, as some imidazolium salts are ionic liquids, we have shown that these ionic liquids can act as phase-segregated precatalyst reservoirs for polymerization reactions.<sup>6</sup> More recently, active carbene catalysts have been thermally generated from neutral haloalkane adducts of NHCs and used in the polymerization of lactide.<sup>7</sup> However, only saturated carbenes can be delivered in this fashion, and under certain conditions, these compounds were observed to racemize lactide during polymerization. Unsaturated NHCs have been successfully bound to silver, and the resulting complex has been used as a carbene transfer agent to generate transition metal carbene complexes.<sup>8,9</sup> We envisaged that these silver complexes might provide a convenient source of carbenes for organocatalytic applications,<sup>9</sup> as the metal transfer reactions of these complexes occur in mild conditions. Furthermore, the insolubility of silver chloride is expected to provide a favorable driving force for generation of the free carbene.

Three (imidazol-2-ylidene)silver(I) chloride complexes **1a–c** were evaluated for their activity as transesterification catalysts. Compound **1a** is an ionic liquid at room



**1b**: R<sub>1</sub> = R<sub>2</sub> = Me

**1c**: R<sub>1</sub> = *i*-Prop, R<sub>2</sub> = H

temperature, and crystallizes slowly at 10 °C. Compounds **1b** and **1c** are solids at room temperature. The thermal stability of these compounds was studied by differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA). Compounds **1b** and **1c** do not appear to show any significant thermal decomposition below 250 °C in the solid state. Compound **1a**, however, exhibits a large

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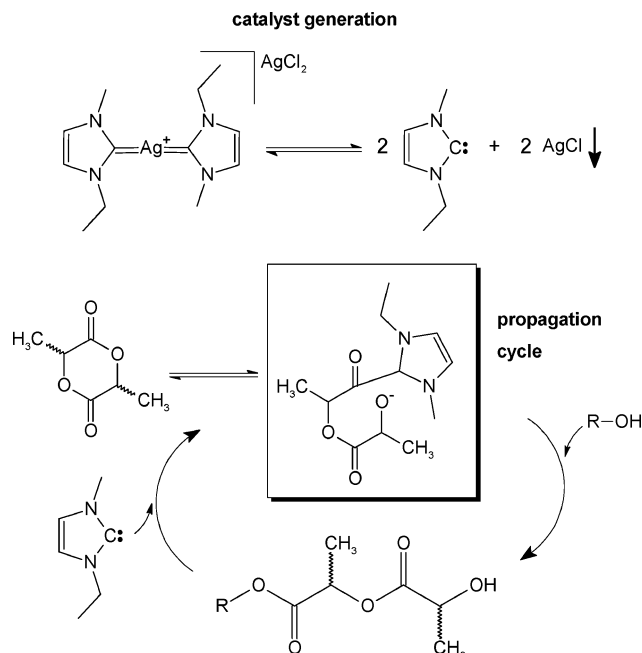
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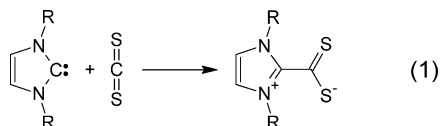
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**SCHEME 1. Carbene-Catalyzed Lactide Polymerization**


endothermic thermal transition at 89.2 °C accompanied by gradual mass loss, which may indicate the generation of free carbene ligands. To determine whether carbene is generated in the thermal decomposition of **1a**, efforts were made to trap the carbene upon thermolysis in solution with carbon disulfide (eq 1).<sup>10</sup> Upon heating with carbon disulfide in THF, compound **1a** forms a red-brown solid that has an NMR signature consistent with a zwitterionic disulfide adduct of a carbene.<sup>7e,10,11</sup>



As these experiments provide evidence that thermolysis of compound **1a** generates the carbene, we evaluated the activity of these silver adducts as catalysts for transesterification reactions and lactide polymerization (Scheme 1). Compound **1a** catalyzes the polymerization of L-lactide at temperatures ranging from 40 °C up to 100 °C. The optimal temperature for the ring-opening polym-

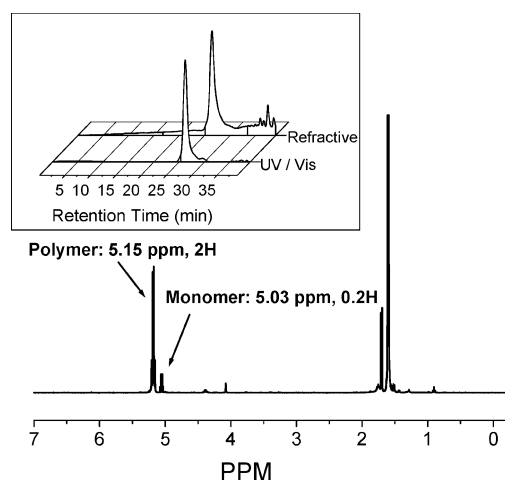
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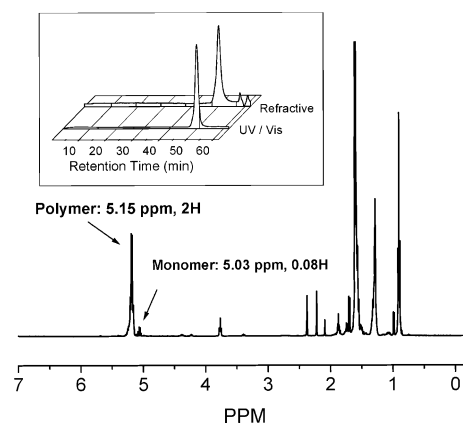
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**FIGURE 1.** NMR and GPC of L-lactide polymerized with compound **1a** at 60 °C for 12 h.



**FIGURE 2.** NMR and GPC of L-lactide polymerized with compound **1b** at 100 °C for 72 h.

erization was 60 °C, which gives 90% conversion after 12 h (Figure 1), to give polymer of  $M_n = 26\,000$  and polydispersity ( $M_w/M_n = 1.12$ ) by gel permeation chromatography (GPC). NMR analysis provided no evidence of racemization of the lactide, whereas under similar polymerization conditions the saturated imidazolin-2-ylidene catalysts led to epimerization of lactide, as evidenced by an  $^1\text{H}$  NMR signal at 5.11 ppm in  $\text{CDCl}_3$  corresponding to the *meso*-lactide. This signal is absent in the polymers catalyzed by compound **1a**.

Compound **1b** also is capable of catalyzing the polymerization of L-lactide. With this catalyst, the reaction is much slower (72 h at 100 °C to give 95% conversion) but yields poly-L-lactide with a narrow molecular weight distribution ( $M_w/M_n = 1.17$ ) (Figure 2). While no strong thermal transitions are observed by DSC for compound **1b** in the solid state at this temperature, it is likely that in solution a small concentration of free carbene is produced and can catalyze the polymerization reaction. Alternatively, the silver carbene might polymerize lactide directly, but further studies are warranted to address the nature of the active catalysts under these conditions.

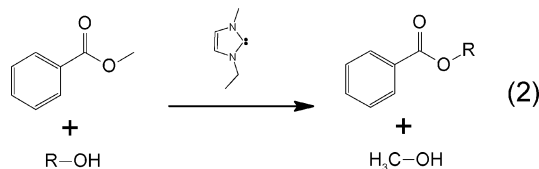
When polymerization is initiated from 1-pyrenebutanol, the resultant polymers show similar traces in the GPC traces with UV (254 nm) and refractive index detection. This indicates that the pyrenebutanol is

**TABLE 1. Transesterification Results for Compound 1a**

R =	% conversion	
	after 18 h	after 48 h
ethyl	84	96
isopropyl	6	15
tert-butyl	0	~2

homogeneously distributed in the polymer sample, consistent with initiation of the chains from pyrene butanol (Figures 1 and 2, inset).

To test the general utility of silver–NHC complexes, compound **1a** was also examined as a catalyst for small molecule transesterifications (eq 2). Methyl benzoate was



heated with various alcohols in the presence of compound **1a**, and the resulting mixture analyzed by NMR (Table 1). This reaction proceeds for primary alcohols with 78% conversion to ethyl benzoate at 70 °C in the presence of ethanol after 18 h. The reaction proceeds more slowly with secondary alcohols,<sup>12</sup> proceeding with 15% conversion after 48 h. With tertiary alcohols transesterification is extremely slow, providing only 2% conversion after 48 h at 70 °C.

In summary, we have demonstrated that silver carbene complexes are competent catalysts for the ring-opening polymerization of lactide, as well as the transesterification of methyl benzoates. The methyl- and ethyl-substituted compound **1a** undergoes thermal decomposition at 90 °C to give 1-ethyl-3-methylimidazol-2-ylidene, which can be used to as a transesterification catalyst. As a precatalyst for the polymerization of L-lactide, compounds **1a** and **1b** produce materials with low PDI and do not cause racemization of the monomer.

## Experimental Section

**General Procedure for Formation of Carbene–Silver Complexes: (1-Ethyl-3-methylimidazol-2-ylidene)silver Chloride (1a).** 1-Ethyl-3-methyl-1-*H*-imidazolium chloride (0.800

g, 5.46 mmol) was dissolved in 100 mL of CH<sub>2</sub>Cl<sub>2</sub>, and silver(I) oxide (0.632 g, 2.73 mmol) was added to the stirring solution. The mixture was stirred for 48 h and filtered, and the product was precipitated in *n*-pentane. No further purification was necessary (1.328 g, 96%). <sup>1</sup>H NMR (CDCl<sub>3</sub>) δ 1.42 (t, 3H), 3.80 (s, 3H), 4.12 (q, 2H), 6.97 (d, 1H), 6.99 (d, 1H). <sup>13</sup>C NMR (CDCl<sub>3</sub>) δ 17.4, 39.2, 47.3, 53.9, 100.0, 120.9, 122.7, 179.8. MS calcd for C<sub>12</sub>H<sub>20</sub>AgN<sub>4</sub><sup>+</sup> 327.07, found 327.1.

**General Procedure for in Situ Catalyst Formation and L-Lactide Polymerization.** In a glovebox, a vial equipped with a stirbar was charged with (1-ethyl-3-methylimidazol-2-ylidene)silver chloride (14.0 mg, 27.7 μmol), 1-pyrenebutanol (4.13 mg, 13.9 μmol), L-lactide (400 mg, 2.77 mmol), and 2 mL of dry toluene. The vial was then heated and stirred. The vial was cooled to room temperature, 3 mL of THF was added, and the solution was added dropwise to stirring hexanes to precipitate the polymer. The polymer was washed with hexanes, filtered, and dried.

**Procedure for Carbene Trapping with Carbon Disulfide.** In the glovebox, a vial equipped with a stirbar was charged with (1-ethyl-3-methylimidazol-2-ylidene)silver(I) chloride (30.0 mg, 0.591 mmol). THF (2 mL) was added, then carbon disulfide (90.0 mg, 1.18 mmol). The mixture was heated to 60 °C for 6 h, at which time the reaction mixture turns red. The product was precipitated in hexanes, and isolated as a red-brown solid. <sup>1</sup>H NMR (acetone-*d*<sub>6</sub>) δ 1.46 (t, 3H), 3.74 (s, 3H), 4.17 (q, 2H), 7.37 (d, 1H), 7.43 (d, 1H). <sup>13</sup>C NMR (CDCl<sub>3</sub>) δ 16.0, 29.4, 35.1, 44.3, 119.0, 121.2, 227.1.

**Procedure for Transesterification of Methyl Benzoate.** In a glovebox, a vial with a stirbar was charged with (1-ethyl-3-methylimidazol-2-ylidene)silver(I) chloride (7.00 mg, 14.6 μmol), methyl benzoate (0.100 g, 0.734 mol), and ethanol (0.338 g, 7.34 mmol). Toluene (1 mL) was added, the vial was sealed and heated to 100 °C for 18 h. The solvent was evaporated, and the products were assayed by NMR.

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**Supporting Information Available:** Details of the synthesis of **1b** and **1c**, <sup>1</sup>H and <sup>13</sup>C spectra for **1a,b,c**.<sup>13</sup> This material is available free of charge via the Internet at <http://pubs.acs.org>.

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