Copper Complexes with N-Alkylated NS_2-Macrocyclic Ligands: Synthesis, Characterization, and Capabilities as Aziridination Precatalysts

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Received July 9, 2004

The syntheses of two new ligands containing macrocyclic [10]-aneNS_2 (1-aza-4,8-dithiacyclodecane) units are reported, including the N-methylated analogue ($\mathbf{L}^{Me}$) and a dinucleating version that separates two [10]-aneNS_2 groups with a *m*-xylyl spacer ($\mathbf{L}^2$). Copper complexes with these new ligands as well as previously reported related complexes have been found to mediate the aziridination of olefins. Thus, isolated copper complexes containing the ethylnaphthyl-appended [10]-aneNS_2 macrocyclic ligand ($\mathbf{L}^{nap}$), including [$\mathbf{L}^{nap}$Cu]PF_6 (**1**) and [$\mathbf{L}^{nap}$Cu(CH_3CN)]PF_6 (**2**), the Cu(I) complex [$\mathbf{L}^{Me}$Cu(CH_3CN)]PF_6 (**3**), and the Cu(II) complex $\mathbf{L}^{Me}CuBr_2$ (**4**), were compared in their ability to function as aziridination precatalysts. In addition, the aziridination capabilities were probed for complexes generated in situ from copper(I) ion sources and $\mathbf{L}^2$, 1,4,7-triazacyclononane, 1,4,7-trithiacyclononane, or 1,4,7-trimethyl-1,4,7-triazacyclononane. The synthesis and characterization of the new complexes **3** and **4** are reported, including X-ray crystal structures. The aziridination reaction using precatalyst **3** was examined for its tolerance to different functional groups near the olefin as well as to the use of other nitrogen group sources and reaction conditions.

Introduction

Aziridines are saturated three-membered rings containing one nitrogen atom. These compounds possess a strained ring and, thus, are susceptible to ring-opening reactions. This reactivity makes aziridines useful synthetic intermediates to organic chemists and provides biological activity for some natural products: for instance, the mitomycins.[1] Nonracemic aziridines are especially desirable in the field of stereoselective synthesis and have been utilized as chiral substrates, auxiliaries, reagents, and/or ligands.[2]

In 1991, Cu(I) and Cu(II) salts were reported to be catalytically active in the aziridination of alkenes.[3,4] Copper complexes, including [$Cu(CH_3CN)_4$]ClO_4 and Cu(acac)$_2$ (acac = acetoacetonate ligand), gave superior results[4] compared to the manganese[5,6] and iron[7] systems previously reported as aziridination catalysts. Subsequently, additional nitrogen-, oxygen-, or halide-ligated copper complexes have been described as aziridination catalysts[8−19] and the subject has been covered in several reviews.[20−23] However, these systems suffer from some deficiencies, most notably, low or no yields of aziridine with some substrates.

Jacobsen and co-workers determined that at least one open coordination site at the copper ion was essential for aziridination reactivity in their system, as a tetradentate salen-based complex yielded no aziridine products while a complex of an analogous bidentate ligand catalyzed aziridination.[10] More recently, Halfen described a tetradentate-ligated copper system that

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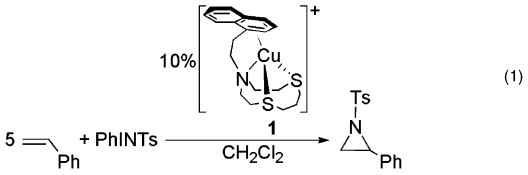
10.1021/om040098g CCC: $27.50
Publication on Web 09/29/2004

catalyzed aziridination more sluggishly than an analogous tridentate-ligated system, which was suggested to be due to a slow ligand arm dissociation step,[24,25] and Handy and co-workers reported a bidentate-ligated copper system that gave higher yields than an analogous tridentate-ligated system.[26] A few years ago, we reported a new ethylnaphthyl-appended [10]-aneNS$_2$ macrocyclic ligand ($\mathbf{L}^{nap}$) that allowed the formation of an unusual copper η^2-naphthalene complex, [$\mathbf{L}^{nap}$Cu]PF$_6$ (**1**).[27,28] The copper−naphthalene binding in **1** was found to be weak,[28,29] providing at least one readily accessible coordination site in **1** available for exploitation. We now report that **1** is a competent precatalyst for the aziridination of a range of olefins using the typical conditions reported in those earlier studies: 5 equiv of olefin, 0.1 equiv of precatalyst, and 1 equiv of the nitrogen source *N*-(*p*-toluenesulfonyl)imino)phenyliodinane (PhINTs)[30,31] (eq 1).



(1)

To investigate the importance of the easily dissociable arene group in **1**, the aziridination capabilities of a complex where the naphthalene had been displaced with an acetonitrile ligand, [$\mathbf{L}^{nap}$Cu(CH$_3$CN)]PF$_6$ (**2**), were explored. The aziridination reactions catalyzed by complexes with the new ligand $\mathbf{L}^{Me}$, which incorporates an *N*-methyl group in place of the pendant ethylnaphthyl group, were also examined, including with the Cu(I) complex [$\mathbf{L}^{Me}$Cu(CH$_3$CN)]PF$_6$ (**3**) and the Cu(II) complex $\mathbf{L}^{Me}$CuBr$_2$ (**4**). In addition, a new dinucleating ligand ($\mathbf{L}^2$) was synthesized to compare the aziridination efficiencies of similar mononuclear and dinuclear copper precatalysts. The aziridination capabilities of these complexes are reported here, as well as the synthesis and characterization of the new ligands $\mathbf{L}^{Me}$ and $\mathbf{L}^2$ and complexes **3** and **4**.

Experimental Section

Materials and Procedures. All reagents were used as received from Aldrich, Acros, EM, Fischer, or Spectrum, except *cis*-stilbene and styrene, which were purified by reduced-pressure distillation. The syntheses of the copper complexes were performed under a nitrogen atmosphere using standard Schlenk and glovebox techniques; all other syntheses were open to the air unless otherwise stated. All solvents were distilled from the following drying agents and were kept over molecular sieves until use: CH$_3$CN and CH$_2$Cl$_2$ with calcium hydride, CH$_3$NO$_2$ with magnesium sulfate, and Et$_2$O from sodium/benzophenone. The compounds [$\mathbf{L}^{nap}$Cu]PF$_6$ (**1**),[27,32] [$\mathbf{L}^{nap}$Cu(CH$_3$CN)]PF$_6$ (**2**),[27,32] [Cu(CH$_3$CN)$_4$]PF$_6$,[33] PhINTs,[30] Cu(acac)$_2$,[34] [CuOTf]$_2$·C$_6$H$_6$ (OTf = triflate ion),[35,36] and 1-aza-4,8-dithiacyclodecane[37] were synthesized as reported. Vacuum-filtration chromatography was performed with Selecto Scientific IB2 TLC silica gel; the R_f value is for the given solvent system on Baker-Flex silica gel IB2-F TLC plates.

Physical Measurements. ^{1}H and ^{13}C NMR spectra were taken with a General Electric QE 300 MHz, a Bruker Avance 400 MHz, or a Varian Unity Plus 500 MHz FT-NMR spectrometer; chemical shifts were referenced to the residual proton or carbon resonance of CDCl$_3$ (^{1}H, 7.26 ppm; ^{13}C, 77.2 ppm) or CD$_3$NO$_2$ (^{1}H, 4.33 ppm; ^{13}C, 61.4 ppm). IR spectra were recorded on a Nicolet Protégé 460 FT-IR spectrometer as neat films unless otherwise stated and are reported in cm^{-1}. UV−vis spectra were taken with a Hewlett-Packard 8452A diode-array spectrophotometer and reported with λ_{max} in nm and ϵ in M^{-1} cm^{-1}. GCMS data were recorded on a Hewlett-Packard Model 5890 gas chromatograph (acetone solvent; HP-1 cross-linked methyl silicone gum 25 m × 0.25 mm × 0.11 μm column; He carrier gas; 80 °C for the first 3 min, then ramped at 10 °C/min up to a maximum temperature of 280 °C) coupled with a Hewlett-Packard 5970 series mass spectrometer. FABMS measurements were performed by the University of California, Riverside, Mass Spectrometry Facility on their VG-ZAB mass spectrometer. Elemental analyses of solid samples were completed by NuMega Resonance Labs, Inc. (San Diego, CA); the ligands were isolated as oils that contained small but variable amounts of solvents that were difficult to remove and, thus, no elemental analyses are reported for these compounds. A Johnson-Matthey magnetic susceptibility balance was used for the magnetic measurement. Melting points were determined in an open capillary tube on a Thomas-Hoover Model 6406-H melting point apparatus and are uncorrected. The solution conductivity measurements were made with a Corning Model 311 conductivity meter.

Crystallographic Studies. Suitable crystals were mounted with silicone caulk to a glass fiber on the benchtop. The data were collected with a Siemens P4 diffractometer with a graphite monochromator at ambient temperatures from 3.5 to 47° in 2θ for **3** and from 3.5 to 45° in 2θ for **4** and $\pm h$, $+k$, $+l$ quadrants for both. The structures were solved with Patterson methods followed by subsequent cycles of least-squares refinement and calculation of difference Fourier maps. The data were refined (full-matrix least squares on F^2) with the Siemens SHELXTL version 5.0.3 PC software package using literature scattering factors,[38] including its ψ-scan-based semiempirical absorption correction. Neither structure required an extinction correction. All non-hydrogen atoms were modeled anisotropically. Hydrogen atoms were placed at calculated distances and use a riding model, which means that the positional and thermal parameters are derived from the carbon atom each hydrogen atom is bound to, while maintaining the calculated distance and optimal angles. No peaks or holes greater than 0.55 e/Å^3 remained in the final difference maps for the structures, except a peak of 0.77 e/Å^3 in **3** near a disordered PF$_6^-$, for which the disorder was not modeled. In the structure of **3** there are two independent [$\mathbf{L}^{Me}$Cu(CH$_3$CN)]$^+$ molecules and three positions containing the two PF$_6^-$ ions;

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two of those positions lie on symmetry elements and are, therefore, of half-occupancy.

Preparation of 1-Methyl-1-aza-4,8-dithiacyclodecane (L^{Me}). To 1-aza-4,8-dithiacyclodecane (1.35 g, 7.6 mmol) was added a solution of formaldehyde (37% aqueous solution, 36 mL, 0.48 mol), formic acid (88% aqueous solution, 70 mL, 1.6 mol), and water (9 mL). The solution was heated under reflux for 24 h and was then cooled to room temperature. The resulting clear solution was poured into 70 mL of water, and the pH was adjusted to 12 by the addition of solid NaOH. The cloudy solution was then extracted with $CHCl_3$ (3 × 75 mL). The organic fractions were combined, washed with a 10% NaOH solution, dried ($MgSO_4$), and concentrated to a yellow oil. Further purification by vacuum-filtration chromatography (50:50 ethyl acetate/hexane eluent, $R_f = 0.83$) gave $\mathbf{L}^{Me}$ (0.93 g, 4.9 mmol, 66%) as a clear oil. ^{1}H NMR (CD_3NO_2): δ 3.04 (m, 4 H, CH_2NCH_2); 2.67 (m, 8 H, CH_2SCH_2CH$_2$CH_2SCH_2); 2.25 (s, 3 H, NCH_3); 1.87 (m, 2 H, CH$_2$CH_2CH$_2$). ^{13}C NMR (CD_3NO_2): δ 59.2 (2 C, CH$_2$NCH$_2$); 41.5 (1 C, NCH$_3$); 31.7, 29.7 (2 C ea, CH$_2$SCH$_2$CH$_2$$CH_2SCH_2$); 30.6 (1 C, CH$_2$$CH_2CH_2$). GCMS ($t_{ret}$ = 12.2 min; m/z): 191 (M^+, 60%), 98 (95%), 71 (100%). UV−vis (THF, nm): 230 (1410), 248 sh. IR (cm^{-1}): 2944 vs, 2914 vs, 2836 s, 2785 vs, 2714 m, all ν(C−H$_{aliph}$); 1457 s; 1419 s; 1369 m; 1354 mw, 1298 s; 1255 m; 1204 w; 1175 w; 1119 m; 1082 w; 1061 m; 1011 m; 950 w; 944 w; 940 w; 916 w; 840 w; 780 w; 774 w; 752 w; 736 w; 689 w; 645 w.

Synthesis of the Diamide Precursor to L^2. The macrocycle 1-aza-4,8-dithiacyclodecane (1.79 g, 10 mmol) was dissolved in 15 mL of toluene, and the solution was cooled to 0 °C. To that solution 4.2 mL (30 mmol) of Et_3N was added, followed by the dropwise addition of a solution of isophthaloyl dichloride (0.97 g, 4.8 mmol) in toluene (15 mL), causing the immediate appearance of an off-white solid. The resulting suspension was stirred overnight and warmed to room temperature. The solids were then filtered away, and the solvent was removed by distillation. The resulting oil was dissolved in 80 mL of $CHCl_3$. This solution was washed with a 10% NaOH solution (4 × 125 mL) and then dried ($MgSO_4$). The solvent was removed to give a yellow oil, which was purified by vacuum-filtration chromatography (ethyl acetate eluent, R_f = 0.43). After several hours drying in vacuo, the diamide compound was isolated in 50% yield (1.16 g, 2.4 mmol) as a white solid. ^{1}H NMR ($CDCl_3$): δ 7.71 (s, 1 H, CH_{arom2}); 7.67 (d, 2 H, J = 8 Hz, C$H_{arom4,6}$); 7.41 (t, 1 H, J = 8 Hz, CH_{arom5}); 3.78, 3.45 (m, 4 H each, 2 × CH'_2NCH_2); 3.19 (m, 8 H, 2 × CH'_2CH$_2$CH_2); 3.08, 2.93 (m, 4 H each, 2 × S−CH'_2CH$'_2$-NCH$_2$CH_2S); 1.84 (m, 4 H, 2 × CH$'_2$CH_2CH$_2$). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 172.8 (2 C, 2 × C=O); 136.9 (2 C, $C_{arom1,3}$); 128.6 (2 C, CH$_{arom4,6}$); 128.5, 126.2 (1 C each, CH$_{arom2,5}$); 52.3 (4 C, 2 × CH$_2$NCH$'_2$); 35.8, 32.7, 31.0, 30.6 (br, 4 C each, 2 × C'H$_2$SC$'$H$_2$-CH$_2$CH$_2$SCH$_2$); 29.3 (2 C, 2 × CH$'_2$$CH_2CH_2$). IR ($cm^{-1}$): 3050 w ν(C−H$_{arom}$); 2963 ms ν(C−H$_{aliph}$); 2921 s ν(C−H$_{aliph}$); 2853 w ν(C−H$_{aliph}$); 1717 m; 1660 ms; 1634 s ν(C=O); 1579 m; 1542 w; 1480 w; 1456 m; 1439 ms; 1409 ms; 1355 m; 1295 m; 1261 s; 1208 w; 1113 m; 1087 m; 1021 m; 938 w; 917 vw; 803 ms; 763 w; 733 m; 700 m; 633 vw.

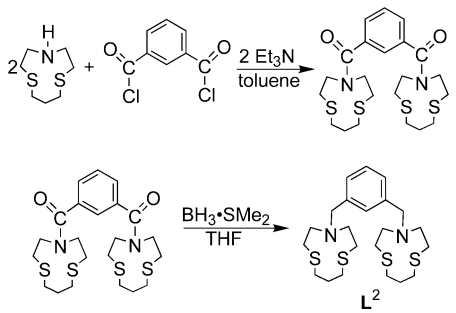
Synthesis of 1,3-Phenylenebis(1-aza-4,8-dithiacyclodecane) (L^2). Under a dinitrogen atmosphere, the diamide from the preceding paragraph (0.645 g, 1.3 mmol) was cooled to 0 °C and 10 mL (20 mmol) of BH_3·SMe_2 (2 M solution in THF) was added dropwise. The resulting solution was slowly warmed and then heated at reflux for 1 h. After the solution was recooled to 0 °C, 15 mL of a 1.6 M HCl solution was added dropwise. The THF and SMe_2 were removed by distillation, and the remaining solution was made basic by the addition of solid NaOH. The product was extracted into $CHCl_3$ (3 × 45 mL), which was then dried ($MgSO_4$). The solvent was removed to give $\mathbf{L}^2$ as a colorless oil in 88% yield (0.54 g, 1.2 mmol). ^{1}H NMR ($CDCl_3$): δ 7.44 (s, 1 H, CH_{arom2}); 7.29 (m, 3 H, C$H_{arom4,5,6}$); 3.61 (4 H, 2 × PhCH_2N); 3.23 (t, 8 H, J = 6 Hz, 4 × NCH_2CH$_2$S); 2.80 (d, 8 H, J = 5 Hz, 2 × CH_2CH$_2$CH_2); 2.66 (d, 8 H, J = 6 Hz, 4 × NCH$_2$CH_2S); 1.89 (q, 4 H, J = 5 Hz, 2 × CH$_2$CH_2CH$_2$). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 138.5 (2 C, $C_{arom1,3}$); 130.6, 128.1 (1 C each, CH$_{arom2,5}$); 128.3 (2 C, CH$_{arom4,6}$); 59.4 (2 C, 2 × PhCH$_2$N); 56.7 (4 C, 4 × CH$_2$$CH_2$N); 32.8, 30.5 (4 C each, 2 × CH$_2$SCH$_2$CH$_2$$CH_2SCH_2$); 30.3 (2 C, 2 × CH$_2$$CH_2$-CH$_2$). IR ($cm^{-1}$): 3054 w ν(C$_{arom}$−H); 3025 ms ν(C$_{arom}$−H); 2918 s ν(C−H$_{aliph}$); 2794 s ν(C−H$_{aliph}$); 2721 ms; 2672 m; 1607 w; 1590 w; 1488 ms; 1456 s, 1441 s, 1418 s; 1369 s; 1343 s; 1327 s; 1296 s; 1283 s; 1263 s; 1250 s; 1214 ms; 1191 m; 1123 s; 1103 s; 1088 s; 1027 s; 993 ms; 959 ms; 941 ms; 923 ms; 842 m; 801 s; 776 ms; 743 s; 700 ms; 671 w; 651 w; 604 w.

Preparation of [L^{Me}Cu(CH$_3$CN)]PF$_6$ (3). A solution of the ligand $\mathbf{L}^{Me}$ (0.93 g, 4.9 mmol) dissolved in CH_2Cl_2 (50 mL) was added dropwise over 5 min to [Cu(CH$_3$CN)$_4$]PF$_6$ (1.81 g, 4.9 mmol). The resulting cloudy solution was stirred for 5 h and then filtered. Removal of the solvent from the clear filtrate yielded a light yellow solid that was dried in vacuo for 3 h. Two subsequent reprecipitations with CH_3CN/Et_2O gave analytically pure **3** (1.94 g, 3.3 mmol, 68%). ^{1}H NMR (CD_3NO_2): δ 3.30 (m, 2 H, SCHH$'$CH$_2$CHH$'$S); 3.09 (m, 6 H, N CHH$'$C-HH$'$SCHH'CH$_2$CHH'SCHH$'$CHH$'$N); 2.85 (m, 2 H, CHH'SCH$_2$-CH$_2$CH$_2$SCHH'); 2.74 (m, 2 H, CHH'NCHH'); 2.70 (s, 3 H, NCH_3); 2.32 (m, 1 H, SCH$_2$CHH$'$CH$_2$S); 2.26 (s, 3 H, NCCH_3); 1.88 (m, 1 H, SCH$_2$CHH'CH$_2$S). ^{13}C NMR (CD_3NO_2): δ 119.3 (1 C, C≡N); 54.0 (2 C, CH$_2$NCH$_2$); 45.1 (1 C, NCH$_3$); 35.7 (2 C, SCH$_2$CH$_2$$CH_2$S); 32.9 (2 C, 2 × NCH$_2$$CH_2$S); 25.1 (1 C, SCH$_2$$CH_2CH_2$S); 0.9 (1 C, H$_3$$C$-C≡N). IR ($cm^{-1}$): 2961 m, 2945 m, 2917 m 2853 m ν(C−H$_{aliph}$); 2315 w (ν(C−C) + δ(CH$_3$)); 2282 w ν(C≡N); 1463 vs; 1417 s; 1372 w; 1305 s; 1270 m; 1230 m; 1207 w; 1175 m; 1132 w; 1093 s; 1080 s; 1046 s; 1020 s; 991 m; 949 m; 936 w; 917 w; 844 vs (PF_6^-); 733 s; 701 w; 622 w. UV−vis (THF): 220 (2400) 256 sh. FABMS (m/z): 254/256 [$\mathbf{L}^{Me}$Cu]$^+$. Anal. Calcd for $C_{10}H_{20}N_2CuF_6PS_2$: C, 27.21; H, 4.57; N, 6.35. Found: C, 27.43; H, 4.72; N, 6.69. Mp: 161−163 °C dec.

Preparation of $L^{Me}CuBr_2$ (4). A solution of $\mathbf{L}^{Me}$ (0.38 g, 2.0 mmol) in MeOH (15 mL) was added dropwise over 5 min to a solution of $CuBr_2$ (0.44 g, 2.0 mmol) in MeOH (15 mL). The resulting deep green solution was stirred for 45 min, precipitating a dark orange-brown solid. The solids were isolated by filtration and were dried in vacuo for 5 h, giving analytically pure **4** (0.73 g, 1.8 mmol, 87%). UV−vis (CH_3NO_2, nm (ϵ, M^{-1} cm^{-1})): 386 (2.7×10^3), 440 sh, 530 (430); 726 (270). IR (Nujol, cm^{-1}): 1412 s; 1397 m; 1342 w; 1306 w; 1286 m; 1222 m; 1204 m; 1138 w; 1121 w; 1078 m; 1043 w; 1014 m; 985 m; 946 s; 937 m; 912 m; 892 s; 835 m; 823 m; 806 w; 734 s. μ_{eff} = 1.9 μ_B (298 K). Anal. Calcd for $C_8H_{17}NBr_2S_2$: C, 23.31; H, 4.16; N, 3.40. Found: C, 23.17; H, 3.92; N, 3.21. Mp: 176−177 °C dec.

Aziridination Reactions. The aziridination of styrene is given as a prototypical example. To a solution of styrene (5 equiv) in 8 mL of CH_3NO_2 was added the copper precatalyst (0.1 equiv) and PhINTs (1 equiv) at ambient temperature. The resulting green slurry was stirred until the solution became homogeneous, at which time Ph_3CH (1 equiv) was added as an internal standard. The solution was then concentrated to dryness and analyzed by NMR spectroscopy. The aziridine yield was determined by integration of the products in the ^{1}H NMR spectrum of the crude reaction mixture versus the methine proton of Ph_3CH and is quoted versus the PhINTs limiting reagent unless stated otherwise. The use of Et_2O to dissolve the organics away from the copper product(s) and the filtration of the solution through a silica plug were also explored. These routes were discarded in favor of spectroscopically analyzing the products directly in most cases, because some aziridines were partially decomposed by those conditions and gave significantly reduced yields after those workup procedures. The presence of the small amount of Cu(II) ion did not influence the spectra or yields (consistently varied ≤3%) in several reactions analyzed both before and after the

Scheme 1. Synthesis of the New Dinucleating Ligand L^2



ether-dissolution or silica-column workup methods (tested with aziridines that were stable to those workup conditions).

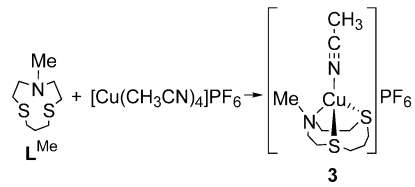
The turnover aziridination reactions for both complexes were set up concurrently in a fashion similar to that described above. However, once all of the PhINTs had dissolved, a small amount of each solution was removed for spectroscopic analysis. Additional aliquots of PhINTs, styrene, and Ph_3CH standard were then added to the remaining solutions and the reactions continued. The process of analysis, followed by addition of more substrate, was continued until the reactions were stopped at an arbitrary time. The amount of time necessary for the PhINTs to dissolve increased steadily from about 5 min for the first aliquot to nearly 30−35 min by the fifth aliquot.

Results and Discussion

Synthesis and Characterization of the Ligand L^{Me}. The new macrocyclic ligand 1-methyl-1-aza-4,8-dithiacyclodecane (L^{Me}) was synthesized in four steps with an overall yield of about 21%. The first three steps produce the [10]-aneNS$_2$ macrocycle, as reported by Chandrasekhar and McAuley.[37] In the last step, the secondary amine in [10]-aneNS$_2$ was methylated with excess formaldehyde and formic acid by a method similar to that used for other aza macrocycles.[39] Purification of the resulting product by vacuum-filtration chromatography provided L^{Me} as a colorless oil. The macrocycle L^{Me} is soluble in a variety of organic solvents, including benzene, Et_2O, MeOH, THF, CH_3NO_2, and $CHCl_3$. ^{1}H and ^{13}C NMR spectra and the observation of a weak molecular ion in the mass spectrum of L^{Me} are consistent with the 1-methyl-1-aza-4,8-dithiacyclodecane formulation.

Synthesis and Characterization of the Ligand L^2. The new dinucleating ligand 1,3-phenylenebis(1-aza-4,8-dithiacyclodecane) (L^2) was generated in two steps (Scheme 1) from 1-aza-4,8-dithiacyclodecane in 44% yield (~14% for all five steps, including macrocycle synthesis). In the first step, 2 equiv of the macrocyclic precursor was reacted with isophthaloyl dichloride in toluene to give a diamide compound. This diamide compound was reduced with borane−dimethyl sulfide complex in THF to produce L^2 as a colorless oil. The compound L^2 was characterized by ^{1}H and ^{13}C NMR as well as IR spectroscopy. L^2 is soluble in solvents such as $CHCl_3$, THF, and CH_2Cl_2 and is insoluble in more polar solvents, including CH_3CN.

Synthesis and Characterization of [L^{Me}Cu(CH_3CN)]PF_6 (3). The stoichiometric reaction (eq 2) of L^{Me} and [Cu(CH_3CN)$_4$]PF_6 in either CH_3CN or CH_2Cl_2 produces [L^{Me}Cu(CH_3CN)]PF_6 (**3**) as a light yellow solid in 68% yield after workup. Consistent with the ionic nature of the complex, **3** is soluble in polar solvents such as CH_3NO_2, DMSO, and CH_3CN and is insoluble in less polar solvents, including benzene and Et_2O. Complex **3** is air stable as a solid and in CH_3CN solution (or solutions with added CH_3CN) for at least 3 h. However, **3** is somewhat air sensitive in solution when not in the presence of added CH_3CN: for instance, turning a green color consistent with oxidation to Cu(II) in $CHCl_3$ after being opened to the air for 30 min.



(2)

Complex **3** has been fully characterized, including by IR and ^{1}H and ^{13}C NMR spectroscopy, FABMS, elemental analysis, and X-ray crystallography (Table 1). Ligation of the Cu(I) ion in solution is suggested by an observation of diastereotopic splitting of the resonances for the L^{Me} macrocyclic ring protons in the ^{1}H NMR spectrum as well as by shifting of the resonances for the same protons in **3** compared to free L^{Me}. For example, the two protons on the central carbon of the propylene bridge appear in L^{Me} as a single resonance at 1.9 ppm in CD_3NO_2 but split into two distinct multiplets in **3**, centered at 2.2 and 1.8 ppm. The coordinated acetonitrile ligand gives two weak bands in the IR spectrum of **3** at 2315 and 2282 cm^{-1}. These absorptions occur in the typical range for transition-metal−NCCH$_3$ complexes, between about 2270 and 2300 cm^{-1},[40] and are reasonable for a copper−acetonitrile complex.[32]

Table 1. Crystallographic Data for 3 and 4

	[L^{Me}Cu(CH_3CN)]PF_6 (**3**)	$L^{Me}CuBr_2$ (**4**)
chem formula	$C_{10}H_{20}CuF_6N_2PS_2$	$C_8H_{17}Br_2CuNS_2$
formula wt	440.91	414.71
cryst color and habit	colorless plate	orange block
dimens (mm)	0.78 × 0.62 × 0.08	0.50 × 0.28 × 0.20
T (°C)	24	26
λ, Å	0.710 73 (Mo Kα)	0.710 73 (Mo Kα)
space group	$P2_12_12_1$ (No. 19)	$P2_12_12_1$ (No. 19)
a (Å)	15.917(2)	7.7942(6)
b (Å)	30.197(4)	12.6656(14)
c (Å)	7.3647(6)	13.8021(14)
α, β, γ (deg)	90	90
V (Å^3)	3539.7(7)	1362.5(2)
Z	8	4
D_{calcd} (g/cm^3)	1.655	2.022
transmission factors	0.5207−0.8599	0.2189−0.3492
μ (mm^{-1})	1.611	7.740
no. of rflns measd	3641	1469
no. of indep rflns	3426	1327
R_{int}	0.0439	0.0224
R1 [a]	0.0555	0.0367
wR2[b]	0.1590	0.0842

[a] R1 = $\sum||F_o| - |F_c||/\sum|F_o|$ (observed data, $I > 2\sigma(I)$). [b] $wR2 = [\sum[w(F_o^2 - F_c^2)^2]/\sum[w(F_o^2)^2]]^{1/2}$ (all data).

(39) Barefield, E. K.; Wagner, F. *Inorg. Chem.* **1973**, *12*, 2435−2439.

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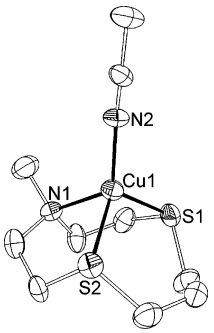
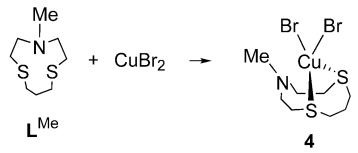


Figure 1. Thermal ellipsoid plot of the solid-state structure of **3**, showing one independent cationic portion at the 25% probability level. Hydrogen atoms are omitted for clarity. Selected bond distances (Å) and angles (deg): Cu1−S1, 2.282(3); Cu1−S2, 2.301(4); Cu1−N1, 2.158(10); Cu1−N2, 1.907(10); C≡N, 1.114(13); N1−Cu1−N2, 120.2(4); S1−Cu1−S2, 109.15(14); S1−Cu1−N1, 90.7(3); S1−Cu1−N2, 119.3(3); S2−Cu1−N1, 89.8(3); S2−Cu1−N2, 120.6(3); C−C≡N, 179.5(15); Cu1−N≡C 171.8(11).

Slow diffusion of Et_2O into a saturated CH_3CN solution of **3** yielded colorless single crystals as plates that were suitable for crystallographic structure determination. The asymmetric unit contains two independent molecules of the cationic portion of **3** (one is shown in Figure 1). The only significant difference between the two structures is the position of the central propylene carbon atom in the macrocyclic ring. Thus, in one independent molecule that carbon atom is directed toward the copper center and in the other molecule that carbon atom points away from the coordination sphere. Both copper ions are four-coordinate, as is typical for Cu(I),[41,42] bound by the three heteroatoms from the macrocyclic ring as well as the nitrogen atom from the acetonitrile ligand. The geometry about the copper ions is best described as distorted tetrahedral, with all copper−ligand angles found between 122.5(3) and 89.8(3)° and averaging to indistinguishable values (108.3 and 108.2°) for the two cations. All of the Cu−S distances are essentially identical (2.266(4)−2.301(4) Å), whereas the two kinds of Cu−N distances are distinctly different, as expected ($Cu-N_{macrocycle}$ near 2.15 Å and $Cu-N_{acetonitrile}$ closer to 1.93 Å). All of the distances and angles within the macrocyclic and acetonitrile ligands appear to be unexceptional.[28,32]

The most abundant copper-containing ion observed in the positive ion FAB mass spectrum for **3** corresponds to the cationic portion of **3** minus the acetonitrile ligand, $[\mathbf{L}^{Me}Cu]^+$. However, the acetonitrile ligand in **3** is not easily lost in the absence of other more strongly coordinating ligands under normal conditions. For example, no detectable loss of CH_3CN occurred upon applying a vacuum to **3** for 5 h at ambient temperatures. This contrasts to the facile loss of the acetonitrile ligand observed for the ethylnaphthyl-appended [10]-aneNS_2 ligated acetonitrile complex **2**, which relatively easily dissociates the acetonitrile ligand to generate the naphthalene-bound complex **1**.[27,28]

Synthesis and Characterization of $\mathbf{L^{Me}CuBr_2}$ (4). The addition of equimolar amounts of $\mathbf{L}^{Me}$ and $CuBr_2$ in MeOH (eq 3) precipitated the dark orange-brown solid $\mathbf{L}^{Me}CuBr_2$ (**4**) in 87% yield. Complex **4** is soluble in relatively polar solvents, including CH_3NO_2, DMSO, and DMF, and is somewhat soluble in water but is insoluble in less polar solvents such as CH_2Cl_2, Et_2O, and pentane. The presence of the copper ion was confirmed by a magnetic susceptibility measurement of 1.9 μ_B, consistent with one unpaired electron, as required for the Cu(II) formulation. Complex **4** is stable indefinitely to air as a solid and is also reasonably stable in solution, including to several equivalents of H_2O overnight at room temperature in CH_3NO_2.



(3)

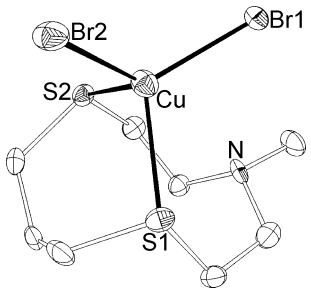


Figure 2. Thermal ellipsoid plot of the solid-state structure of **4** at the 25% probability level. Hydrogen atoms are omitted for clarity. Selected bond distances (Å) and angles (°): Cu−S1, 2.374(3); Cu−S2, 2.347(3); Cu−Br1, 2.410(2); Cu−Br2, 2.393(2); S1−Cu−S2, 99.20(10); S1−Cu−Br1, 115.86(9); S1−Cu−Br2, 101.55(8); S2−Cu−Br1, 102.60(8); S2−Cu−Br2, 110.61(9); Br1−Cu−Br2, 124.39(7).

Single crystals for X-ray crystallography (Table 1) were grown by the cooling and then partial evaporation of a warm saturated CH_3CN solution of **4**. The solid-state structure (Figure 2) shows the geometry about the copper(II) ion to be distorted tetrahedral with angles that occur between 124.39(7) and 99.20(10)° and average to 109.0°. Distorted-tetrahedral Cu(II) complexes are typically compressed.[42] Complex **4** is modestly compressed compared to most structurally characterized Cu(II) complexes, as seen by the dihedral angle of 82.3° between the Br_2Cu and S_2Cu planes. The Cu−Br distances in **4** are slightly different from one another and are normal for four-coordinate Cu−Br complexes, as seen for 22 such complexes surveyed in 1989 that displayed an average Cu−Br distance of 2.393(42) Å.[43] Two sulfur atoms from the macrocyclic ring complete the coordination sphere around the copper ion in **4** with Cu−S distances of 2.347(3) and 2.374(3) Å. Interestingly, the nitrogen atom of the macrocyclic ring doesnot seem to interact with the copper center in **4**; the Cu−N distance of 3.333 Å is too long to be considered a bond.

Conductivity experiments suggest that the bromide ligands in **4** dissociate in polar solvents to different extents, depending on the solvent properties. Thus, in DMF the molar conductivity of **4** is similar to that of $^nBu_4NBr$, consistent with the dissociation of one bro-

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Table 2. Relative Results of Styrene Aziridination Reactions Using Different Precatalysts

precatalyst	aziridine yield[a]
$Cu(acac)_2$	100
$[\mathbf{L}^{nap}Cu]PF_6$ (**1**)	97
$[\mathbf{L}^{nap}Cu(CH_3CN)]PF_6$ (**2**)	98
$[\mathbf{L}^{Me}Cu(CH_3CN)]PF_6$ (**3**)	100
$[\mathbf{L}^{Me}Cu(PhCH_2CH_2)]PF_6$	99
$\mathbf{L}^2 + [Cu(CH_3CN)_4]PF_6$	86
$\mathbf{L}^{Me} + (CuOTf)_2{\cdot}C_6H_6$	95
$\mathbf{L}^{Me} + Cu(OTf)_2$	92
$\mathbf{L}^{Me} + [Cu(CH_3CN)_4]PF_6$	96
$\mathbf{L}^{Me} + Zn(OTf)_2$	0
$\mathbf{L}^{nap} + AgPF_6$	0
tacn + $[Cu(CH_3CN)_4]PF_6$	103
Me_3-tacn + $[Cu(CH_3CN)_4]PF_6$	84
ttcn + $[Cu(CH_3CN)_4]PF_6$	63
$\mathbf{L}^{Me}CuBr_2$ (**4**)	87

[a] Aziridine yields are given relative to those for $Cu(acac)_2$ (i.e., as (aziridine yield for the reaction using the stated precatalyst)/(aziridine yield for the reaction using $Cu(acac)_2$ as the precatalyst) × 100) in an experiment run concurrently with $Cu(acac)_2$ and under the same, but not necessarily optimized, conditions. These reactions utilized 1 equiv of PhINTs, 5 equiv of styrene, and 0.1 equiv of precatalyst in CH_3NO_2 under ambient conditions and for which $Cu(acac)_2$ produced 90% of the aziridine in an optimized reaction.

mide ion. In contrast, the molar conductivity of **4** in CH_3NO_2 was more than 70% lower than in DMF, suggesting that the complex is only partially ionized in CH_3NO_2. In addition, the molar conductivity of **4** in H_2O was consistent with the presence of three ions, indicating the dissociation of both bromide ligands.

Influence of the Precatalyst on the Aziridination Reaction. As mentioned above, the naphthalene-bound complex **1** is a competent precatalyst for the aziridination of styrene at room temperature (eq 1). The reaction produced an amount of aziridine (87% in CH_3NO_2; relative to PhINTs) comparable to that of the reaction catalyzed by $Cu(acac)_2$ under nearly the same conditions in our laboratory (90% in CH_2Cl_2; 95% reported[12]). The aziridination reaction of styrene mediated by **1** proceeds rapidly and is finished in less than 5 min (these reactions are typically monitored by visually following the disappearance of PhINTs; PhINTs is nearly insoluble in the solvents employed for the reactions and dissolves as it reacts).

To address whether the presence of the labile arene group is a desirable or necessary feature of the catalyst, the aziridination reactions of styrene catalyzed by **1**−**3** were compared under the same conditions (Table 2). The yields and reaction times were essentially identical for those three complexes, indicating that the arene ligand was not needed, as it could be replaced with an CH_3CN ligand or even totally removed, as in **3**. Therefore, the focus was shifted away from the more synthetically demanding complexes **1** and **2** to the equally catalytically effective but more easily prepared complexes with $\mathbf{L}^{Me}$. The styrene complex $[\mathbf{L}^{Me}Cu(PhCHCH_2)]PF_6$ [44] was also synthesized and partially characterized. Aziridination reactions with this complex determined that precoordination of the olefin to the precatalyst makes little difference in the reaction results (Table 2). This is consistent with a mechanism where copper−alkene coordination is not part of the rate-limiting step, such as that proposed by Brandt and co-workers.[45]

The dinucleating ligand $\mathbf{L}^2$ was synthesized to probe whether a dinuclear copper complex would give better aziridination results than a mononuclear complex. In this system, however, the dinuclear complex did not appear to be a better aziridination precatalyst (Table 2). Presumably this is either because two metal centers in close proximity do not catalyze this aziridination reaction better than an isolated metal-containing site or because the methylene groups allowed the two copper centers to swivel away from one another such that the two copper-containing sites essentially acted independently. Others have reported that dinuclear complexes are slow and give poor enantiomeric excesses as aziridination catalysts[46] or result in a moderate improvement in copper-catalyzed cyclopropanation.[47]

For the reactions of **1**−**3**, PhINTs, and styrene carried out under a N_2 atmosphere, the solution turned blue-green immediately and remained blue-green at the conclusion of the reaction as well, consistent with the presence of at least some Cu(II) ion. Therefore, the aziridine-forming capability of the precatalysts formed in situ from $\mathbf{L}^{Me}$ and either a Cu(I) or Cu(II) starting complex was also probed. The results (Table 2) suggest that it does not matter significantly whether a Cu(I) or Cu(II) starting material, or a preformed complex, is used for the aziridination catalysis. This observation has also been made by Evans for Cu(I) and Cu(II) bis(oxazoline) triflate complexes.[12] The proposal that Cu(I) is the resting state and that the catalyst cycles between Cu(I) and Cu(III) with a Cu(II) entry point in the mechanism is consistent with these results.[45] However, the presence of the copper ion was essential to aziridine formation, as no aziridine was produced in analogous reactions containing zinc or silver ions (Table 2).

Nearly all accounts of copper-catalyzed aziridination reactions use nitrogen and/or oxygen-ligated complexes; only one reports the use of a sulfur-ligated precatalyst, to our knowledge, and found that the ligand was transformed in the reaction.[48] Since the use of a sulfur-ligated (or partially sulfur-ligated) complex to mediate this process appeared unusual, the influence of the ligating atoms on the aziridination yields was also probed. Thus, the aziridination capabilities of precatalysts formed in situ with $[Cu(CH_3CN)_4]PF_6$ and the commercially available macrocyclic ligands 1,4,7-triazacyclononane (tacn), 1,4,7-trithiacyclononane (ttcn), and 1,4,7-trimethyl-1,4,7-triazacyclononane (Me_3-tacn) were compared (Table 2). The reactions were run in pairs versus $Cu(acac)_2$, whose ability as an aziridination precatalyst has been well established and for which reaction conditions can be optimized to give 90−95% aziridine yields.[4,21]

$Cu(acac)_2$ always gave the best yields *when the reactions were allowed to continue for the same period of time* (30 min, more than enough time for the PhINTs to completely dissolve in all cases). However, the reac-

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tion times between the different complexes varied significantly, as determined by visually watching the PhINTs dissolve, and were consistently about 20 min for $Cu(acac)_2$ and 10 min or less for **3** plus the precatalysts formed from the commercial macrocyclic ligands (**3** appeared to be the fastest). The aziridine yields were much higher for the reactions of the precatalysts other than $Cu(acac)_2$ when the reactions were worked up immediately after all of the PhINTs had dissolved, as compared to the yields for the same reactions left for 30 min. For instance, the aziridine yield from the reaction using $[Cu(CH_3CN)_4]PF_6$ and tacn slightly exceeded that of $Cu(acac)_2$, which is consistent with the report by Halfen and co-workers that copper complexes of *N*-isopropyl-substituted triazacyclononane are efficient aziridination catalysts.[49] Thus, depending on the sensitivity of the aziridine product, copper-catalyzed reactions should be closely monitored and terminated at the appropriate time for the highest aziridine yields. Others have suggested that the copper catalyst may be decomposed by the aziridine product in copper-catalyzed aziridination reactions.[45]

The nature of the counterion does not strongly influence these aziridination reactions, as long the counterion is very weakly coordinating or is noncoordinating. Thus, the counterions PF_6^- and OTf^- gave essentially identical results. In contrast, the bromide ligand influences the aziridination reaction, as **4** reacts more slowly and gives a lower yield than other Cu(II) systems containing $\mathbf{L}^{Me}$ (Table 2). The reaction of **3**, styrene, and PhINTs in CH_3NO_2 to which 2 equiv of $^nBu_4NBr$ (relative to **3**) was also added gave only a trace amount of aziridine, and when 10 equiv of $^nBu_4NBr$ was added, no aziridine product was observed. Other copper halide complexes have been reported to react more slowly and give poorer enantiomeric excesses.[11]

To determine if the macrocyclic ligands in **1**−**4** remained associated with the copper ion, and to see if a reaction occurred at the ligands, any free organic compounds were separated from the inorganic complexes after the aziridination reactions starting with those complexes. To do this, diethyl ether was used to dissolve the organic compounds. Alternatively, the organic products were separated on a silica column; however, treatment with silica has been reported to decompose some of the aziridine- or copper-containing products.[50] Free ligands were not detected with either method, suggesting that the macrocyclic ligands remain associated with the copper ions.

The copper ion was then removed from the postcatalytic copper-containing product(s) and separated from its ligands by use of an $NH_3(aq)/CH_2Cl_2$ extraction (the cupric ion is liberated into the ammonia solution, forming the bright blue hexaammine complex, and the ligand is extracted into the organic layer). ^1H NMR spectroscopy and GCMS confirmed isolation of unaltered $\mathbf{L}^{nap}$ and $\mathbf{L}^{Me}$ from these reactions. These results suggest that at the conclusion of the reaction the ligands were associated with the copper ion and were unchanged by the catalytic process; i.e., ligand sulfur oxidation and naphthyl group aziridination did not occur (assuming that any reaction product of the ligand either survives the copper ion removal process or is converted to a different species than the starting ligand; for instance, sulfilimines are stable to hydrolysis in basic solutions but are hydrolyzed under forcing acidic conditions to give sulfoxides[51]). Although naphthyl groups have not been found to react under these aziridination conditions, naphthalene aziridination has been reported under different conditions.[52] In addition, PhINTs has been reported to oxidize DMSO[12] and cause multiple nitrene insertions to generate a tetraamido complex from a Cu(I) bis(dithiocarbamate) complex.[48] In contrast to the results with $\mathbf{L}^{nap}$ and $\mathbf{L}^{Me}$, the acac ligands from $Cu(acac)_2$ may be liberated or modified during the aziridination reaction, as IR spectra of the postcatalytic copper-containing product(s) do not contain strong, distinctive acetoacetonate C−O bands.

Influence of the Reaction Conditions on the Aziridination Results. This system gave the best aziridine yields using CH_3NO_2 as the solvent and similar or slightly reduced yields in CH_3CN. The use of CH_2Cl_2 tended to lower the product yields by about 10%. This is comparable to the results reported for most other copper aziridination catalysts, where polar solvents, especially CH_3CN, were found to give the fastest and highest-yielding reactions for most substrate alkenes.[12] Dried solvents are necessary for the reaction: for instance, the addition of 3 equiv of water to the styrene reaction with **3** decreased the yield of the aziridine product to ca. 10%. Performing the reaction in the presence of activated molecular sieves and/or adding the nitrogen source in several portions instead of at once also improved aziridine yields in some instances.

PhINTs[4,10,50] and its analogues[53,54] are effective nitrogen sources for aziridination; however, they are fairly expensive to make. The less expensive, commercially available oxidizing agent Chloramine-T ($TsNClNa\cdot 3H_2O$)[55] has been reported to give modest yields of aziridines as a nitrogen source in copper-catalyzed aziridination reactions[56,57] as well as for aziridination reactions not requiring a d-block metal ion.[58,59] Both precatalysts **3** and $Cu(acac)_2$ gave very poor aziridine yields (3 and 18%, respectively) with styrene as the substrate in the presence of Chloramine-T·$3H_2O$ in CH_2Cl_2 (CH_3NO_2 is incompatible with $TsNCl^-$), presumably largely due to the water introduced by the Chloramine-T·$3H_2O$. The use of the anhydrous Chloramine-T derivative $^nBu_4NTsNCl$[60,61] increased the aziridine yield

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Table 3. Results of Aziridination Reactions for Cyclohexene and 3

amt of cyclohexene (equiv)	*T* (°C)	−NTs source	aziridine product (%)	allylic insertion (%)	tosylamine (%)
5	23	PhINTs	18	0	30
200	23	PhINTs	20	30	20
5	−18	PhINTs	15	4	23
200	−18	PhINTs	18	<3	35
5	23	*p*-NO_2PhINTs	24	0	3
200	23	*p*-NO_2PhINTs	17	26	39
5	−18	*p*-NO_2PhINTs	22	0	10
200	−18	*p*-NO_2PhINTs	13	0	0
5	23	*p*-CH_3OPhINTs	22	0	15
200	23	*p*-CH_3OPhINTs	36	0	16
5	−18	*p*-CH_3OPhINTs	30	0	9
200	−18	*p*-CH_3OPhINTs	26	0	15

for the reactions of **3** and $Cu(acac)_2$ with styrene to 50% and 25%, respectively. Reports of higher aziridination yields using other halide derivatives of Chloramine-T have appeared, including Bromamine-T[62,63] and a potassium iodide derivative.[64] In addition, alternative methods using the PhINTs oxygen analogue iodosylbenzene and sulfonylamines to form aziridines[65,66] and a soluble PhINTS analogue have been reported.[67]

The yields of aziridine derived from the reactions of cyclohexene catalyzed by **1**−**4** (18−20%) were substantially less than that for styrene (85−88%) using the same reaction conditions. It is common in copper systems to see lower aziridine product yields from alkyl-substituted olefin reactants: for example, Halfen's group found modest to no yields of such aziridine products in reactions mediated by copper complexes of tetradentate nitrogen ligands.[24] Since the aziridine yields were low in these reactions, some reaction conditions were varied to try to improve the yield (Table 3, first four columns). Using **3** as the precatalyst, the yields were determined at a lower temperature, at a significantly higher cyclohexene concentration, and by using *p*-nitro- and *p*-methoxy-substituted analogues of PhINTs that have been reported to increase the yields in other systems.[53,68]

In all but one set of experiments the aziridine yields at −18 °C were lower than the yields at 23 °C, although in most cases that difference was within experimental error. The yields resulting from the use of different cyclohexene equivalents also depended on the nitrogen precursor that was utilized. The aziridine yields were usually the highest from reactions using the nitrogen source *p*-CH_3OPhINTs. However, the highest overall yield among these conditions investigated was a modest 36%. The highest yield reported for the copper-catalyzed aziridination of cyclohexene of which we are aware is 93%,[69] although we have seen a yield as high as 71% (see below).

Table 4. Yields from the Aziridination Reactions Using Precatalyst 3

substrate	aziridine yield (%)
styrene	87
styrene	90[a]
cyclohexene	18 (30, allylic amination)
cyclohexene	71[a]
1-hexene	33[b]
methyl cinnamyl ether	55 (17, allylic amination)[b]
cyclopentene	23
1,4-cyclohexadiene	35 (monoaziridine)
1,2-dihydronaphthalene	60[a]
2-methyl-1,3-pentadiene	51 (5:1 at terminal:internal C=C)
ethyl sorbate	55 (at terminal C=C only)
trans-3-heptene	56 (trans)
cis-3-heptene	74 (cis)
trans-*β*-methylstyrene	68 (trans)[b]
cis-*β*-methylstyrene	47 (9:1 cis:trans)[b]
stilbene (cis or trans)	0
2-vinylpyridine	60

[a] Olefin limiting (PhINTs in excess) as opposed to the other experiments, where PhINTs is limiting and the olefin was in excess. [b] Reactions performed in CH_3CN instead of CH_3NO_2.

An allylic amination side product was sometimes observed in cyclohexene aziridination reactions catalyzed by **3** (Table 3, fifth column). This result has been occasionally reported by others using copper systems[12,57] and is more frequently observed in aziridination reactions involving other metal catalysts. This type of product was only observed for cyclohexene and methyl cinnamyl ether (Table 4) but not with other cyclic substrates such as cyclopentene plus the diolefin 1,4-cyclohexadiene (Table 4), for which only a single aziridination occurred even when the amount of PhINTs was doubled. This is similar to the results reported by Knight and Muldowney for a variety of dienes.[50] In addition, nonolefinic substrates known to undergo facile allylic amination reactions, such as ethylbenzene, did not react. The allylic amination product for cyclohexene was seen in CH_3NO_2 but not in CH_2Cl_2, suggesting that the solvent plays some role in facilitating the formation of this product. The solvent CH_3NO_2 appears to react with the Cu-catalyst/PhINTs system, as several equivalents of PhINTs will dissolve in CH_3NO_2 without any other substrate added (with other solvents, for instance, CH_2Cl_2, the PhINTs only seems to dissolve upon reaction with added substrate). Decomposition of PhINTs in CH_3CN has been reported and was suggested to be accompanied by deprotonation of the CH_3CN.[4] Also, the amount of the NTs group (11−87%) detected in the products frequently falls short of that added for low-yielding and slower reactions, such as those with cyclohexene. Obviously, these reactions would need to be examined in more detail to identify where the remaining NTs equivalents have gone.

Reactions were investigated using excess PhINTs (4−10 equiv) instead of olefin. These conditions could be appropriate for the aziridination of a valuable olefin, instead of maximizing the yield of the aziridine from 1 equiv of the PhINTs reagent and several equivalents of olefin, as is usually the case. The yields of aziridine

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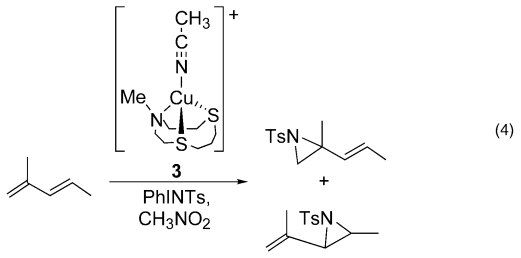
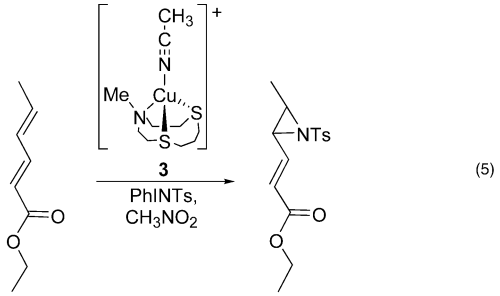
product are good to excellent in the reaction catalyzed by **3** in the presence of excess PhINTs (Table 4). However, to obtain the best yields, the reaction time for each olefin must be monitored carefully, as the aziridine yield reaches a maximum and then decreases. For instance, in the reaction of **3**, ~5 equiv of PhINTs, and cyclohexene in CH_3NO_2, the amount of aziridine in solution was the highest near 17 min into the reaction, but by 1 h the yield of aziridine had decreased by one-third. After 24 h, there was no detectable aziridine product in that reaction mixture.

Capabilities of the System. The aziridination reactions of 2-methyl-1,3-pentadiene (eq 4; Table 4) and ethyl sorbate (eq 5; Table 4) show that this system preferentially reacts with terminal olefins. This is



(4)



(5)

similar to the preferences reported for $Cu(acac)_2$.[50] The aziridination reactions of *trans*- and *cis*-3-heptene and *trans*-β-methylstyrene were stereospecific; however, some *trans*-aziridine product was formed from *cis*-β-methylstyrene, and no aziridine products were detected in the reaction of either *cis*- or *trans*-stilbene (Table 4). Other copper systems have been reported to give differing results with *cis*-β-methylstyrene, ranging from all cis aziridination for $Cu(ClO_4)_2$ to more trans than cis products (70:30) for $CuBr_2$. Some copper systems react with the stilbenes, such as $Cu(acac)_2$,[12] and others do not, such as a tris(pyrazolyl)hydroborate-ligated copper complex[9] and a copper complex of a tridentate ligand in a zeolite system.[70]

In addition to esters, this system is tolerant to a proximal pyridine group on the olefin (Table 4). However, no aziridine product was detected in the reactions of cyclohex-2-enone, cyclohex-2-enol, 1-methylcyclohexene, allylamine, allyl alcohol, vinylacetic acid, or acrylamide under similar conditions. Phenyl group substitution adjacent to the olefin did not alter this reactivity, as no aziridine was recovered from the reactions of *trans*-cinnamic acid, *trans*-cinnamaldehyde, and cinnamide. The aziridination of olefins more remote to these functional groups or of olefins containing protected versions of these functional groups may be possible but was not attempted.

The partial catalytic longevities of **3** and $Cu(acac)_2$ were explored through concurrent turnover experiments. The experiment was terminated when **3** had achieved a turnover number in excess of 150. At that time, complex **3** displayed higher aziridine yields (average yields of aziridine: **3**, 88%; $Cu(acac)_2$, 63%) and a greater overall turnover number than $Cu(acac)_2$ (turnover numbers (mmol of aziridine/mmol of catalyst) at the termination of the experiment: **3**, 153; $Cu(acac)_2$, 120). These experiments suggest that the macrocyclic ligand imparts some enhanced stability to the resulting copper aziridination catalyst compared to the acetoacetonate ligand.

Conclusions

Copper complexes with *N*-alkylated [10]-aneNS_2 macrocyclic ligands are competent aziridination precatalysts. The labile arene group found in **1** does not enhance the reactivity over an acetonitrile ligand, and a dinuclear system was no better at catalyzing aziridination than a similar mononuclear system. Complex **3** has aziridination capabilities comparable to those of copper systems containing 1,4,7-triazacyclononane and 1,4,7-trimethyl-1,4,7-triazacyclononane ligands, which all give greater aziridine yields than the system employing 1,4,7-trithiacyclononane. The bromide ligands in **4** contribute to slower aziridination catalysis and lower aziridine product yields. The yield of aziridine based on limiting amounts of olefin starting material is very good using **3** and excess PhINTs; however, the reaction must be carefully monitored, as the aziridine yield reaches a maximum and then decreases significantly over time. This system tolerates alkyl, aryl, ester, and pyridine groups adjacent to the alkene (as long as the steric bulk does not become too large around the alkene) but does not yield any aziridine product with alcohol, acid, amide, amine, or ketone functionalities near the target double bond. The macrocycle imparts stability to the catalyst, as the system using **3** is capable of more than 150 turnovers.

Acknowledgment. We thank the donors of the Petroleum Research Fund, administered by the American Chemical Society, as well as the National Science Foundation (including 400 MHz NMR spectrometer upgrade; award #0079569) and Colby College (including the Natural Science Division) for research support.

Supporting Information Available: Tables of atomic coordinates, isotropic and anisotropic displacement parameters, and all bond distances and angles for complexes **3** and **4**. This material is available free of charge via the Internet at http://pubs.acs.org.

OM040098G

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