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A R T I C L E S

Highly Active Copper-Based Catalyst for Atom Transfer Radical Polymerization

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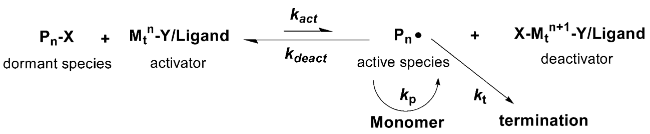
Abstract: Atom transfer radical polymerization (ATRP) generally requires a catalyst/initiator molar ratio of 0.1 to 1 and catalyst/monomer molar ratio of 0.001 to 0.01 (i.e., catalyst concentration: 1000−10 000 ppm versus monomer). Herein, we report a new copper-based complex CuBr/*N*,*N*,*N*′,*N*′-tetrakis(2-pyridylmethyl)-ethylenediamine (TPEN) as a versatile and highly active catalyst for acrylic, methacrylic, and styrenic monomers. The catalyst mediated ATRP at a catalyst/initiator molar ratio of 0.005 and produced polymers with well-controlled molecular weights and low polydispersities. ATRP occurred even at a catalyst/initiator molar ratio as low as 0.001 with copper concentration in the produced polymers as low as 6−8 ppm (catalyst/monomer molar ratio = 10^{-5}). The catalyst structures were studied by X-ray diffraction and NMR spectroscopy. The activator Cu^IBr/TPEN existed in solution as binuclear and mononuclear complexes in equilibrium but as a binuclear complex in its single crystals. The deactivator $Cu^{II}Br_2$/TPEN complex was mononuclear. High stability and appropriate K_{ATRP} (ATRP equilibrium constant) were found crucial for the catalyst working under high dilution or in coordinating solvents/monomers. This provides guidance for further design of highly active ATRP catalysts.

Introduction

Atom transfer radical polymerization (ATRP)[1,2] is a controlled/"living" radical polymerization used extensively for the preparation of homopolymers and random,[3] gradient,[4] block,[5] graft,[6] and dendritic polymers[7] with well-defined structures. ATRP is catalyzed by transition-metal complexes[1,2] such as copper,[8] iron,[9] molybdenum,[10] osmium,[11] and ruthenium[12] that mediate a fast and dynamic equilibrium between the dormant and active polymer chains (Scheme 1).[2] A successful ATRP requires both the activation rate constant k_{act} and the deactivation rate constant k_{deact} to be large enough to establish a fast activation/deactivation equilibrium, but k_{act} should be much smaller than k_{deact} ($k_{act} \ll k_{deact}$) to maintain a good control over the polymerization (eq 1).[2] The equilibrium constant K_{ATRP} ($K_{ATRP} = k_{act}/k_{deact}$) determines the activity of a catalyst and the polymerization rate (R_p). A larger equilibrium constant leads to a higher catalyst activity and a higher polymerization rate.

Scheme 1. ATRP Mechanism



$$R_p = k_p[M][R^\bullet] = \frac{k_p k_{act}[RX]_0[M][Cu^I]}{k_{deact}[Cu^{II}X]}$$

$$PDI = 1 + \left(\frac{k_p[RX]_0}{k_{deact}[Cu^{II}X]}\right)\left(\frac{2}{p} - 1\right) \quad (1)$$

where k_p is the propagation rate constant, k_{act} is the activation rate constant, k_{deact} is the deactivation rate constant, p is the

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monomer conversion, [RX] is the initiator concentration, [M] is the monomer concentration, [$R^\bullet$] is the radical concentration, [Cu^I] is the activator concentration, and [$Cu^{II}X$] is the deactivator concentration.

For most ATRP catalysts, a catalyst concentration in the range of 1000−10 000 ppm (i.e., catalyst/initiator molar ratio of 0.1 to 1 or catalyst/monomer molar ratio of 0.001 to 0.01) is generally needed to provide a controlled polymerization process with a reasonable polymerization rate. These catalysts coprecipitate with the polymer products after polymerization, coloring and contaminating the products. Thus, post-polymerization purification methods[13] and in situ catalyst separations by liquid−liquid[14] and solid−liquid (i.e., solid-supported catalysts)[15] biphasic polymerization have been explored for ATRP to reduce the catalyst residue concentration in the polymers. However, these techniques lead to high costs and scale-up difficulties.[13] The most attractive approach to reduce the catalyst residue in ATRP products is to substantially increase the catalyst activity so that only a very small amount of catalyst is needed to catalyze the polymerization. Thus, no post-purification or catalyst recovery is necessary and the catalyst can be safely and economically left in the polymer products, as in polyolefins.[16]

Copper(I) halides ligated with polydentate amines are widely used as ATRP catalysts due to their availability, versatility, and low cost. The ligands play an important role in the catalytic activity.[2,17] Tetradentate branched ligands form highly active catalysts such as CuBr/tris[2-(*N*,*N*-dimethylamino)ethyl]amine (Me_6TREN) and CuBr/tris(2-pyridylmethyl)-amine (TPMA).[18] While for most catalysts a catalyst/initiator molar ratio (Cu/I) of 1/1 is used, CuBr/Me_6TREN catalyzed polymerizations of methyl acrylate (MA) and butyl acrylate (BA) in a well-controlled manner at a Cu/I ratio of 0.1. The complex also catalyzed a well-controlled ATRP of styrene (St) at a Cu/I ratio of 0.5, but the polymerization at the Cu/I ratio of 0.1 only reached a low conversion and the resulting polystyrene had a high polydispersity index (PDI > 1.5). This catalyst failed to polymerize methyl methacrylate (MMA) at low catalyst concentrations. CuBr/TPMA mediated well-controlled polymerizations of MA and St at a Cu/I ratio of 0.2.[18] It was also reported that CuBr/*N*-tetramethyltriaminephenoxide (Me_4TAPH) catalyzed the polymerization of BA at a Cu/I ratio of 0.05.[18] Guan and Smart found that visible light irradiation increased the catalytic activity of CuCl/2,2′-bipyridine complex for MMA polymerization. At a Cu/I ratio of 0.02 under visible light, the MMA polymerization reached 75% conversion in 16 h.[19] Faucher and Zhu reported that CuBr/1,1,4,7,10,10-hexamethyltriethylenetetramine (HMTETA) polymerized MMA to a low conversion in a controlled/“living” manner at a Cu/I ratio of 0.01.[20] These catalysts, however, could not catalyze “living” polymerizations of MA and St at low catalyst concentrations (e.g., Cu/I $= 0.1$ and 0.01). Ruthenium complexes such as Ru(Cp*)Cl(PPh_3)$_2$ and Ru(2-Me_2N-Ind)Cl(PPh_3)$_2$ (Cp* = pentamethylcyclopentadienyl, Ind = indenyl) were reported to catalyze polymerizations of MA, MMA, and St with good control at a Ru/I = 0.1. [{$RuCl_2$(1,3,5-C_6H_3iPr_3)}$_2$] conjugated with a tricyclohexylphosphine ligand could polymerize MMA in mild conditions with good control over the polymerization at a Ru/I ratio of 0.25, but it could not catalyze polymerizations of MA and St in a controlled/“living” fashion.[21] Recently, a new ATRP initiation method, activator regenerated by electron transfer (AGET), was introduced. It provided a controlled/“living” polymerization of St at a Cu/I ratio of 0.001. In this process, a reducing agent, such as ascorbic acid or tin(II) 2-ethylhexanoate, was needed.[22]

In this study, we report a new copper complex, CuBr/*N*,*N*,*N*′,*N*′-tetrakis(2-pyridylmethyl)ethylenediamine (CuBr/TPEN), as a highly active and versatile ATRP catalyst. Unlike the previously reported bi-, tri-, and tetradentate ligands (e.g., bipyridine, *N*,*N*,*N*′,*N*″,*N*″-pentamethyldiethylenetriamine, TPMA, and Me_6TREN), TPEN is a hexadentate ligand that forms stable complexes with metal ions such as Zn^{2+}, Ni^{2+}, Mn^{2+}, and Fe^{2+} [23] and thus has been used as a metal chelator in medical applications. We found that CuBr formed a [Cu_2Br_2(TPEN)] binuclear complex in the solid state with TPEN. The binuclear complex is in equilibrium with a mononuclear complex in solution, which is highly active and versatile for the polymerizations of MA, MMA, and St.

Experimental Section

Materials. Methyl acrylate (MA, 99%, Aldrich), methyl methacrylate (MMA, 99%, Aldrich) and styrene (St, 99%, Aldrich) were washed with 5 wt % NaOH aqueous solution and twice vacuum distilled over CaH_2 through a Vigreux column. The purified monomers were stored at −15 °C and purged with ultrahigh pure (UHP) argon prior to polymerization. The initiator ethyl 2-bromoisobutyrate (EBiB, 98%, Aldrich) was bubbled with UHP argon before addition to the reaction system. CuBr (99.999%, Aldrich), 2-picolyl chloride hydrochloride (98%, Aldrich), ethylenediamine (99%, Aldrich), $CuBr_2$ (99%, Aldrich), triethylamine (TEA, 98%, Aldrich), tributylamine (TBA, 97%, Aldrich), nitric acid (69.9%, Fisher Scientific), and sodium hydroxide (NaOH, 99.5%, Fisher Scientific) were used as received.

Synthesis of *N*,*N*,*N*′,*N*′-Tetrakis(2-pyridylmethyl)ethylenediamine. The TPEN ligand was synthesized using a method adapted from the literature.[24] 2-Picolyl chloride hydrochloride (20.0 g, 0.12 mol) was

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dissolved in 50 mL of deionized water. The water solution was bubbled with argon for 10 min and cooled in an ice bath. A 5.3 N NaOH aqueous solution (22.5 mL, 0.12 mol) was added to this solution. Ethylenediamine (1.8 g, 0.03 mol) in 100 mL of dichloromethane was then added dropwise to the solution under stirring. After the mixture was stirred at room temperature for 2 days, an additional 5.3 N NaOH aqueous solution (22.5 mL, 0.12 mol) was added, and the lower dichloromethane layer was collected. The dichloromethane solution was washed with an excess of water and dried over molecular sieves. Evaporation of the dichloromethane yielded a brown solid, which was extracted with diethyl ether and further purified by recrystallization in diethyl ether to give 8.0 g (63%) of white or yellowish crystals of TPEN. Mp: 115.5−117.0 °C. ESI-MS: Calcd for $C_{26}H_{28}N_6$: 424.2; found M + Na^+: 447.1. ^{1}H NMR ($CDCl_3$): δ 8.48 (d, 4H, 6-py), 7.56 (m, 4H, 4-py), 7.45 (d, 4H, 3-py), 7.13 (m, 4H, 5-py), 3.77 (s, 8H, N-C*H*$_2$-py), 2.76 (s, 4H, N-C*H*$_2$C*H*$_2$-N). ^{13}C NMR ($CDCl_3$): δ 159.77 (2-py), 148.98 (6-py), 136.33 (4-py), 122.72 (3-py), 121.87 (5-py), 60.84 (N-*C*H$_2$-py), 52.40 (N-*C*H$_2$*C*H$_2$-N).

Polymerizations. Polymerizations at catalyst/initiator molar ratios ranging from 0.1 to 0.01 were conducted in 50-mL Schlenk flasks, and reactions at catalyst/initiator ratios ranging from 0.01 to 0.001 were carried out in 250-mL Schlenk flasks. A typical polymerization procedure of MA at catalyst/initiator ratio of 0.001 was as follows. CuBr (2.87 mg, 0.02 mmol), TPEN (8.48 mg, 0.02 mmol), and a stirring bar were charged into a flask, and the flask was tightly sealed with a rubber septum. Parafilm and PVC tapes were applied to eliminate any potential air ingress. Oxygen was removed from the flask by applying high vacuum and back filling with UHP argon (six cycles). MA (185 mL, 2.0 mol) that had been purged with UHP argon for 2 h was then added through a gastight syringe under the protection of argon. The catalyst solution was colorless or yellowish. After the reaction flask equilibrated to 80 °C in an oil bath, degassed EBiB (3.0 mL, 0.02 mol) was added via a gastight syringe. At timed intervals, samples were withdrawn via degassed gastight syringes under the protection of argon, placed in hermetic vials, and stored in a freezer for NMR and gel permeation chromatography (GPC) measurements. If oxygen or other impurities permeated into the system, the colorless or yellowish solution would change to deep yellow, and the polymerization would slow down or even stop. After the polymerization, some crude polymers were dried under high vacuum for determining the copper content in the polymers. The left crude polymers were precipitated in methanol, and white polymer powders were obtained.

Characterization. ^{1}H NMR and ^{13}C NMR spectra were recorded on a Bruker DRX-400 spectrometer using $CDCl_3$ or acetone-d_6 as solvents. Chemical shift δ was given in ppm referenced to the internal standard tetramethylsilane ($\delta = 0$ ppm). Monomer conversion was determined from the ^{1}H NMR integration ratio of the monomer double bond to methoxyl groups of MA and MMA or phenyl group of St. UV/vis spectra were collected on an Agilent 8453 UV/vis spectrophotometer with ChemStations software for analysis. The number- and weight-average molecular weights (M_n and M_w, respectively) of the prepared polymers were measured by GPC comprised of a Waters SEC equipped with two 300-mm Waters Styragel solvent-saving columns (molecular weight ranges: 5×10^2 to 3×10^4; 5×10^3 to 6×10^5) and a Waters 2414 refractive index detector. The eluent was THF at a flow rate of 0.3 mL min^{-1}, and the column temperature was 30 °C. A series of polystyrene standards with molecular weights ranging from 1250 to 570 000 were employed to generate the universal calibration curves for PMA and PMMA.[25]

The molecular weights of TPEN ligand and its copper complex were measured by an electrospray ionization mass spectrometer (ESI-MS, Finnigan MAT LCQ mass spectrometer) operated in positive-ion mode with source temperature of 200 °C and sample concentration of 100 μM.

Elemental analyses of the copper(II) complex were performed by Midwest Microlab, LLC. The residual copper content in crude polymer products was measured by inductively coupled plasma mass spectrometry (ICP-MS, Perkin-Elmer SCIEX, model ELAN) at the Department of Geology of the University of Wyoming. After the polymerization, the residual monomer was removed under high vacuum. The crude polymer product (100.0 mg) was dissolved in 2.0 mL of nitric acid with heating. The solution was then diluted with deionized water to 10.0 mL for ICP-MS analysis. Another 2.0 mL of nitric acid diluted with deionized water to 10.0 mL was used as blank sample.

X-ray Crystallography. X-ray diffraction (XRD) experiments were performed on a Bruker P4 diffractometer with graphite-monochromatized Mo Kα radiation ($\lambda = 0.71073$ Å) at 25 °C. Single crystals of activator CuBr/TPEN complex were grown by the following procedure. In a glove box filled with UHP argon, CuBr (2.87 mg, 0.02 mmol), TPEN (8.50 mg, 0.020 mmol), and anhydrous acetone (2.0 mL) were charged into a Pyrex 20-mL test tube covered by an aluminum foil with a pinhole. The tube was put into a sealed Erlenmeyer flask containing anhydrous ether. The ether diffused slowly into the test tube through the pinhole, and small yellow block crystals gradually deposited on the side wall of the test tube after four days. A crystal of approximate dimensions $0.32 \times 0.20 \times 0.16$ mm^3 was glued to a glass fiber and used for XRD data collection. A total of 2460 ($R_{\mathrm{int}} = 0.0470$) independent reflections were gathered in the 2θ range of 4.98° to 50°. Full matrix least-squares refinement on F^2 converged to $R_1 = 0.1443$ (all data) and w$R_2 = 0.2008$. All calculations were performed with the SHELXTL-97 package. The crystal structure is in the monoclinic space group *C*2/*c*, with $a = 19.035(3)$ Å, $b = 9.295(2)$ Å, $c = 17.598(3)$ Å, and $\beta = 116.17(1)°$ with $Z = 4$.

The deactivator Cu$^{\mathrm{II}}$Br$_2$/TPEN complex was obtained from the blue precipitates produced during the polymerizations of MA, MMA, and St at catalyst/initiator ratios ranging from 0.1 to 0.01. The blue precipitates were collected and washed with THF in an ultrasonic cleaner. Elemental analysis of the precipitates indicated that the precipitates consisted of CuBr$_2$/TPEN complex at 1/1 molar ratio. About 10 mg of the blue precipitates was dissolved in 2 mL of methanol, and the single crystals of the CuBr$_2$/TPEN complex were grown by slow diffusion of anhydrous ether into the methanol solution as described above. A blue rectangular crystal of approximately $0.16 \times 0.32 \times 0.42$ mm^3 was used for XRD data collection. A total of 5806 ($R_{\mathrm{int}} = 0.0543$) independent reflections were gathered in the 2θ range of 4.24° to 55.02°. Full matrix least-squares refinement on F^2 converged to $R_1 = 0.1215$ (all data) and w$R_2 = 0.1562$. The crystal structure is in the monoclinic space group *P*2$_1$/*c*, with $a = 13.566(3)$ Å, $b = 15.149(2)$ Å, $c = 14.131(2)$ Å, and $\beta = 118.209(13)°$ with $Z = 4$.

Determination of the Activation Rate Constant (k_{act}), Deactivation Rate Constant (k_{deact}), and ATRP Equilibrium Constant (K_{ATRP}). The activation rate constant k_{act} was determined by reacting EBiB with an excess (generally 20-fold to provide pseudo-first-order kinetic conditions) of the CuBr complex and trapping the formed radicals by TEMPO according to the literature method.[26] The equilibrium constant K_{ATRP} for the CuBr/TPEN catalyst was determined by monitoring the EBiB concentration decrease with time according to the recently reported procedure.[27] The K_{ATRP} of another catalyst, CuBr/bis(2-pyridylmethyl)propylamine (BPMPrA), which was synthesized using the literature procedure,[28] was determined by monitoring the accumulation of Cu$^{\mathrm{II}}$Br$_2$/BPMPrA as a function of time during the reaction of EBiB with Cu$^{\mathrm{I}}$Br/BPMPrA complex by UV/vis spectroscopy. The deactivation rate constant k_{deact} was determined indirectly from the known values of K_{ATRP} and k_{act} via $K_{\mathrm{ATRP}} = k_{\mathrm{act}}/k_{\mathrm{deact}}$.

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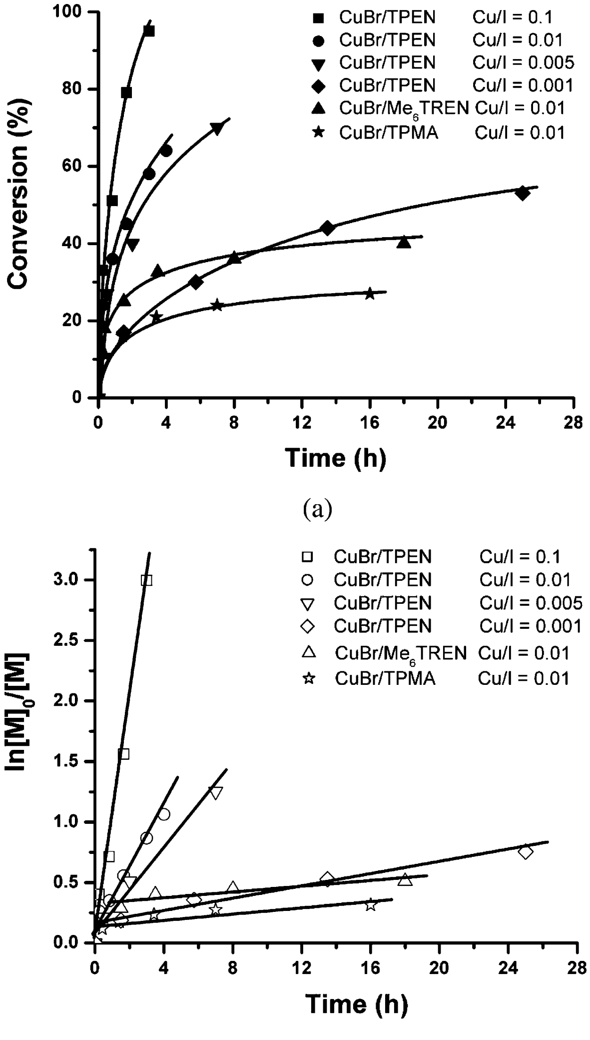


(a)

(b)

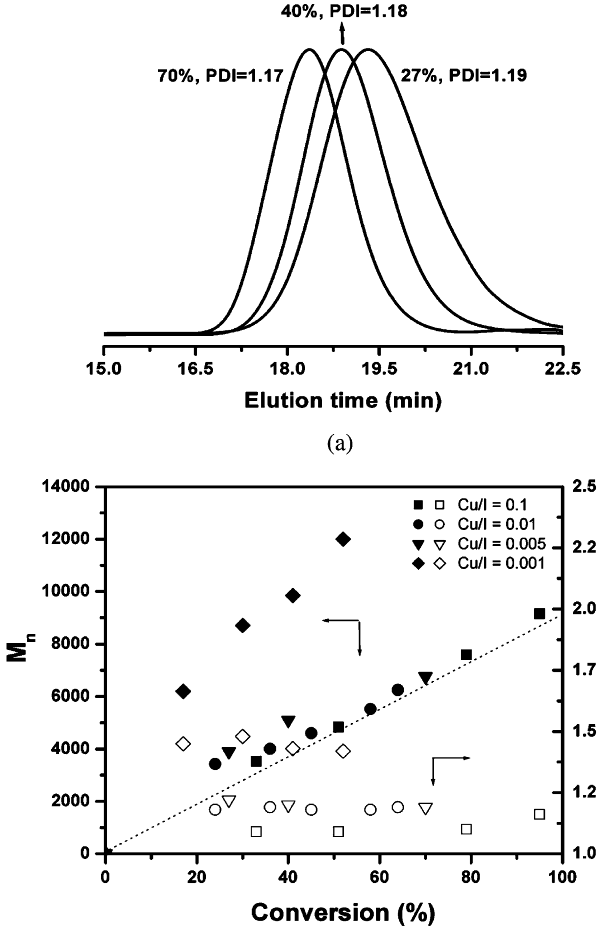
Figure 1. Kinetic plots for ATRP of MA catalyzed by CuBr/TPEN, CuBr/Me$_6$TREN, and CuBr/TPMA. 80 °C, [MA] = 10.8 M, [EBiB] = 0.108 M, Cu/I (i.e., CuBr/EBiB) = 0.1, 0.01, 0.005, and 0.001.

Cyclic Voltammetry (CV). The reduction potential $E_{p,c}$, oxidation potential $E_{p,a}$, and redox potential $E_{1/2}$ of the $Cu^{II}Br_2$/TPEN−$Cu^{I}Br$/TPEN couple and the $Cu^{II}Br_2$/BPMPrA−$Cu^{I}Br$/BPMPrA couple were measured by CV at room temperature with a PGSTAT100 instrument, using General Purpose Electrochemical System version 4.9 AutoLab software. Solutions (1 mM) of $Cu^{II}Br_2$/TPEN and $Cu^{II}Br_2$/BPMPrA were separately prepared in MeCN containing 0.1 M Bu_4NPF_6 as the supporting electrolyte. Measurements were carried out under nitrogen at a scanning rate of 0.1 V s^{-1} using a glassy carbon disk as the working electrode, a platinum wire as the counter electrode, and a saturated calomel reference (SCE) electrode.

Results

ATRP Using CuBr/TPEN as Catalyst. The catalytic activity of CuBr/TPEN was first tested for the ATRP of MA using EBiB as the initiator at varied Cu/I ratios at 80 °C. For comparison, the two reported highly active catalysts CuBr/Me$_6$TREN and CuBr/TPMA[18] were also tested under the identical conditions. Figure 1 shows the plots of conversion and ln([M]$_0$/[M]) versus time, where [M] is the monomer concentration and [M]$_0$ is the initial monomer concentration.

At a Cu/I of 0.1, CuBr/TPEN mediated a rapid polymerization of MA (80% conversion in 1.5 h), producing PMA with a PDI of 1.15 (Figure 2). At the Cu/I ratios of 0.01 and 0.005, the polymerizations were still fast (e.g., 70% conversion in 7 h at Cu/I = 0.005). Even at a Cu/I ratio of 0.001 ([Cu] = 7.4 ppm, catalyst/monomer molar ratio = 10^{-5}), CuBr/TPEN could still catalyze the MA polymerization. The ln[M]$_0$/[M] versus time plots were all linear, indicating that the radical concentration during each polymerization was essentially constant. Under the same conditions, CuBr/Me$_6$TREN and CuBr/TPMA at a Cu/I ratio of 0.01 could only polymerize MA to about 35 and 25% conversions in 16 h and leveled off afterward. At a Cu/I ratio of 0.001, almost no polymerization occurred (<10% conversion). This comparison suggests that CuBr/TPEN had better catalytic performance than CuBr/Me$_6$TREN and CuBr/TPMA at low catalyst concentrations.



(a)

(b)

Figure 2. (a) GPC evolution curves during the polymerization of MA at Cu/I = 0.005. (b) PMA number average molecular weight (M_n) and its PDI (M_w/M_n) as a function of monomer conversions for the ATRP of MA catalyzed by CuBr/TPEN at Cu/I = 0.1 (■,□), 0.01 (●,○), 0.005 (▼,▽) and 0.001(◆,◇). See Figure 1 for conditions.

The molecular weights of the produced PMA from CuBr/TPEN increased linearly with MA conversions, and they remained close to the theoretical values except those from the polymerization at Cu/I ratio of 0.001. The GPC curves of the PMA were monomodal and symmetric, and the polydispersities were less than 1.20 (Figure 2), suggesting that CuBr/TPEN at a Cu/I ratio as low as 0.005 (i.e., catalyst/monomer molar ratio of 5 × 10^{-5}) was adequate to mediate a well-controlled polymerization of MA. The molecular weights of PMA obtained from the polymerization at a Cu/I ratio of 0.001 also increased

Table 1. ATRPs of St and MMA Catalyzed by CuBr/TPEN

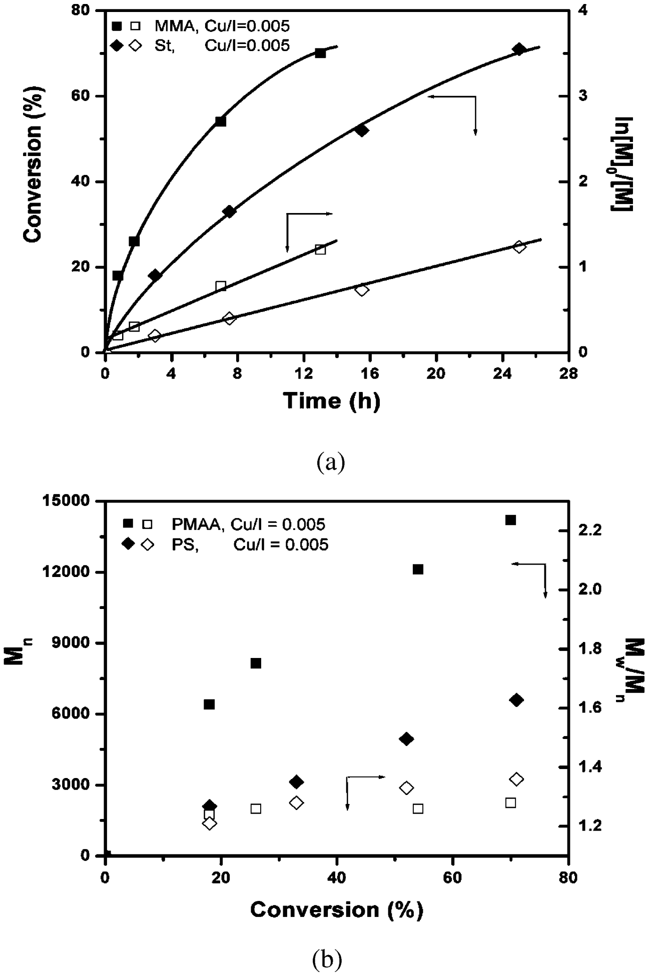
entry	[Cu]/[I]	[Cu] (ppm)	*t* (h)	conv (%)	$M_{n,GPC}$	$M_{n,theo}$[e]	PDI
St[a]	0.01	61.0	20.5	81	6800	8420	1.18
St[a]	0.005	30.5	25.0	71	6600	7380	1.35
St[a]	0.001	6.1	36.0	49	5200	5090	1.66
St[b]	0.005	30.5	22.0	~9			
MMA[c]	0.01	63.3	11.5	73	12000	7300	1.24
MMA[c]	0.005	31.5	13.0	70	14100	7000	1.28
MMA[c]	0.001	6.3	17.0	61	30700	6100	1.34
MMA[d]	0.005	31.5	18.0	14			

[a] 100 °C, [St] = 8.7 M, [EBiB] = 0.087 M, 1 wt % TBA of St. [b] 100 °C, [St] = 8.7 M, [EBiB] = 0.087 M, no TBA. [c] 80 °C, [MMA] = 9.2 M, [EBiB] = 0.092 M, 1 wt % TEA of MMA. [d] 80 °C, [MMA] = 9.2 M, [EBiB] = 0.092 M, no TEA. [e] $M_{n,theo}$ = [monomer]$_0$/[initiator]$_0$ × conversion × monomer molecular weight.

linearly with monomer conversion with PDI of about 1.4, indicating that, even at such a low catalyst concentration ([Cu] = 7.4 ppm), the polymerization was still controlled. The relatively low polymerization rate and initiation efficiency at this concentration may be because, at such a low catalyst concentration, even a trace amount of oxygen or other impurities can cause remarkable chain irreversible terminations and other side reactions and thus decrease the catalyst activity and initiation efficiency.

The polymerizations of MMA and St with CuBr/TPEN as catalyst were also tested. Upon the addition of EBiB to the polymerization solution of MMA or St, a large amount of green solids precipitated from the solution. Elemental analysis of the precipitates showed that the solids were $CuBr_2$ complexed with TPEN at 1/1 molar ratio, which were produced by the atom transfer reaction of EBiB with Cu^IBr/TPEN via persistent radical effect.[2,29] The $Cu^{II}Br_2$/TPEN complex was the deactivator for radicals. A low concentration of $Cu^{II}Br_2$/TPEN was necessary to establish the activation/deactivation equilibrium (Scheme 1) in ATRP.[2] This complex had poor solubility in MMA and St, and thus precipitated out during the polymerization. The precipitation facilitated the reaction of Cu^IBr/TPEN with EBiB and thus converted most of the Cu^IBr/TPEN to $Cu^{II}Br_2$/TPEN, causing low reaction rates or even stopping the polymerization. We found that the addition of tertiary amines such as TEA or TBA could prevent or retard the precipitation of $Cu^{II}Br_2$/TPEN complex and hence increase the polymerization rate. Thus, 1 wt % of TEA (relative to monomer) was added to the MMA monomer. The same 1 wt % of TBA was added to St monomer due to the higher boiling point of TBA. The polymerization results are summarized in Table 1.

Unlike CuBr/Me_6TREN and CuBr/TPMA,[18] CuBr/TPEN exhibited very high activity in MMA and St polymerizations. Similar to the MA polymerization, CuBr/TPEN polymerized St at a Cu/I ratio of 0.005, as shown in Figure 3a. The ln[M]$_0$/[M] versus time plot was linear. The molecular weights of the produced PS increased linearly with styrene conversions and were close to the theoretical values with PDI < 1.35 (Figure 3b). A further decrease of the Cu/I ratio to 0.001 slowed the polymerization, but targeted molecular weights of the PS could still be obtained even though the PDI was relatively high (1.66) (Table 1). This is due to the low radical deactivator concentration at such a low catalyst concentration. At a Cu/I ratio of 0.005, CuBr/TPEN also polymerized MMA smoothly. The ln[M]$_0$/[M] versus time plot was linear but did not pass the origin, indicating irreversible radical terminations at the early stage of the polymerization (Figure 3a). Correspondingly, the molecular weights of the resulting PMMA increased linearly with MMA conversions, but they were higher than the theoretical values (Figure 3b), indicating relatively low initiation efficiency in the MMA polymerization. Even at the Cu/I ratio as low as 0.001, CuBr/TPEN still catalyzed a controlled polymerization of MMA (PDI = 1.34) despite the low initiation efficiency (Table 1). The low initiation efficiency in the MMA polymerization was generally reported when highly active catalyst such as CuBr/Me_6TREN was used.[30] This is because the highly active catalysts such as CuBr/TPEN and CuBr/Me_6TREN have very large ATRP equilibrium constants (K_{ATRP}) in the polymerization of MMA. They rapidly react with the initiators and thus produce a high radical concentration at the early stages of polymerization. Irreversible radical terminations continuously occur at high radical concentrations until a sufficient amount of the deactivator Cu^{II} complex is produced to establish the activation/deactivation



(a)

(b)

Figure 3. (a) Conversion (solid symbols) and ln[M]$_0$/[M] (open symbols) versus time plots for ATRP of St (◆,◇) and MMA (■,□). (b) Molecular weight (M_n, solid symbols) and polydispersity (M_w/M_n, open symbols) as a function of conversion for ATRP of St (◆,◇) and MMA (■,□) catalyzed by CuBr/TPEN at Cu/I = 0.005. St polymerization: 100 °C, [St] = 8.7 M, [EBiB] = 0.087 M, [TBA] = 0.049 M, [CuBr] = [TPEN] = 0.435 mM. MMA polymerization: 80 °C, [MMA] = 9.2 M, [EBiB] = 0.092 M, [TEA] = 0.091 M, [CuBr] = [TPEN] = 0.46 mM.

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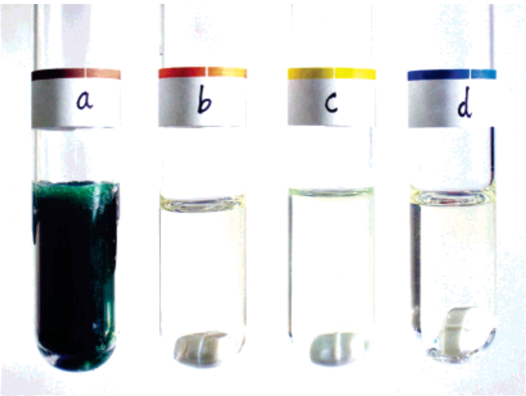

Figure 4. (a) PMMA ([Cu] = 3150 ppm) prepared by CuBr/HMTETA at Cu/I = 0.5, (b) PMMA ([Cu] = 6.9 ppm), (c) PMA ([Cu] = 7.5 ppm), and (d) PS ([Cu] = 6.3 ppm) prepared by CuBr/TPEN at Cu/I = 0.001.

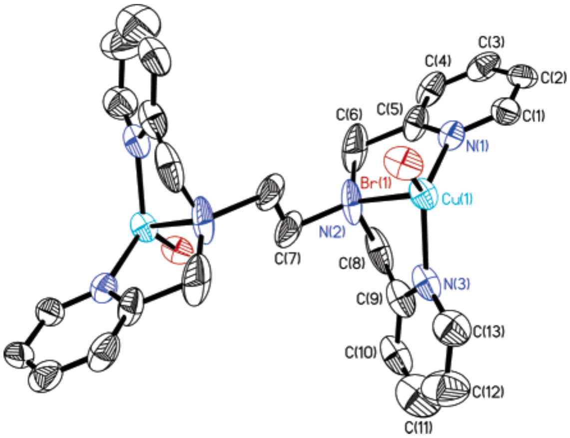

Figure 5. Structure of the [Cu_2Br_2(TPEN)] at a 20% probability level. Hydrogen atoms are omitted, and symmetrically related atoms are unlabeled for clarity. Principal bond lengths [Å] and angles [deg]: Cu(1)−N(1) 2.024(9), Cu(1)−N(2) 2.336(9), Cu(1)−N(3) 2.057(11), Cu(1)−Br(1) 2.327(2), N(1)−Cu(1)−N(3) 119.2(4), N(1)−Cu(1)−Br(1) 120.6(3), N(3)−Cu(1)−Br(1) 119.0(3), N(1)−Cu(1)−N(2) 78.9(4), N(3)−Cu(1)−N(2) 77.7(5), Br(1)−Cu(1)−N(2) 124.4(3).

equilibrium (Scheme 1). A significant amount of initiator was consumed during the irreversible radical terminations, which caused low initiation efficiency in MMA polymerization. The irreversible terminations produced a lot of low molecular weight chains at the early stage of the polymerization, leading to a small population of high molecular weight chains that continued to grow as a controlled polymerization. The low molecular weight polymer chains might not be effectively detected by GPC, which resulted in higher molecular weights of PMMA than theoretical values at low conversions in the initial stage of the polymerization.

The polymers prepared with CuBr/TPEN at the Cu/I ratio of 0.005 and lower are almost colorless (Figure 4b−d). The catalyst concentrations are very low in these polymers. For example, the theoretical copper contents in PMMA are 31.5 ppm at the Cu/I ratio of 0.005, and 6.3 ppm at the Cu/I ratio of 0.001. The copper contents in the PMMA prepared at the Cu/I ratios of 0.005 and 0.001, as measured by ICP-MS, were 33.7 and 6.9 ppm, respectively. This may be low enough to eliminate the need for post-purification and catalyst recovery for most applications, which is a promising milestone toward a commercial ATRP at industrial scale with no need for the removal of catalyst residue.

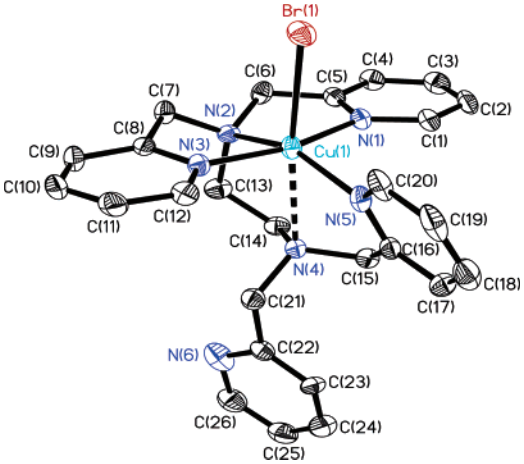

Figure 6. View of the [Cu(TPEN)Br]$^+$ cation at a 30% probability level. Hydrogen atoms are omitted for clarity. Principal bond lengths [Å] and angles [deg]: Cu(1)−Br(1) 2.686(1), Cu(1)−N(3) 2.004(5), Cu(1)−N(1) 2.006(4), Cu(1)−N(5) 2.055(5), Cu(1)−N(2) 2.074(4), Cu(1)−N(4) 2.535(5), N(3)−Cu(1)−N(1) 163.93(18), N(3)−Cu(1)−N(5) 99.84(18), N(1)−Cu(1)−N(5) 96.19(19), N(3)−Cu(1)−N(2) 82.72(18), N(1)−Cu(1)−N(2) 82.33(18), N(5)−Cu(1)−N(2) 154.75(19), N(3)−Cu(1)−N(4) 92.98(16), N(5)−Cu(1)−N(4) 74.08(17), N(2)−Cu(1)−N(4) 80.72(16), N(3)−Cu(1)−Br(1) 91.11(13), N(1)−Cu(1)−Br(1) 86.97(1), N(5)−Cu(1)−Br(1) 100.50(14), N(2)−Cu(1)−Br(1) 104.57(13), N(4)−Cu(1)−Br(1) 173.70(11).

Catalyst Single-Crystal Structures. To understand the exceptionally high activity of the CuBr/TPEN catalyst, single crystals of the catalyst were grown and its solid-state structure was investigated by XRD studies. The XRD data revealed that the single crystal grown from CuBr/TPEN (1/1 molar ratio) had a binuclear [Cu_2Br_2(TPEN)] structure, as shown in Figure 5. The hexadentate TPEN ligand bound two Cu^+ ions using its two sets of bis(2-pyridylmethyl)amino units. The molecule was situated on a twofold symmetry axis with a center of inversion at the center of the bridging diamine ethane C−C bond. The two pyridyl groups, one tertiary amine nitrogen, and one bromide bound the copper center, resulting in a distorted tetrahedral geometry. The Cu−Br distance was 2.327 Å, and the bromide was not involved in any intra- or intermolecular interactions. The Cu−N_{amine} distance was 2.336 Å, significantly longer than the two Cu−$N_{pyridyl}$ bonds (2.024 and 2.057 Å), suggesting a relatively weaker interaction between the copper center and the tertiary amine nitrogen. The distortion from a tetrahedron coordination geometry rendered the N(1)−Cu(1)−N(2) and N(3)−Cu(1)−N(2) angles (78.9° and 77.7°, respectively) more acute than expected (109.5°), whereas the N(1)−Cu(1)−N(3), N(1)−Cu(1)−Br(1), N(3)−Cu(1)−Br(1), and Br(1)−Cu(1)−N(2) angles were opened up remarkably (119.0−124.4°).

Elemental analysis of the Cu^{II} complex isolated from the polymerization solution indicated that the $Cu^{II}Br_2$/TPEN molar ratio was 1/1. The crystals grown from the $Cu^{II}Br_2$/TPEN complex solution indeed had a mononuclear [Cu(TPEN)Br]Br structure (Figure 6). The [Cu(TPEN)Br]$^+$ cation and Br^- anion were well-ordered and separated. The TPEN ligand bound the Cu^{2+} ion using five of its six donor nitrogen atoms. One of the nitrogen atoms, N(4), was weakly coordinated to the copper center, resulting in a highly distorted octahedral geometry for the metal center. Yoon et al. reported that copper(II) perchlorate formed mononuclear [Cu(TPEN)]($ClO4$)$_2$ with TPEN ligand.[31]

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Table 2. K_{ATRP}, k_{act}, and k_{deact} of CuBr/TPEN and Other Copper Catalysts

catalyst	$E_{p,a}$	$E_{p,c}$	$E_{1/2}{}^{a}$	K_{ATRP} (22 °C)	k_{act}, $M^{-1}\ s^{-1}$ (35 °C)	ref
CuBr/bpy	0.145	−0.075	0.035	3.9×10^{-9}	0.066	38−40
CuBr/BPMPrA	−0.044	−0.151	−0.098	6.2×10^{-8}	0.2	this work
CuBr/PMDETA	−0.005	−0.140	−0.075	7.4×10^{-8}	2.7	38−40
CuBr/TPEN	−0.169	−0.242	−0.206	$2.0 \times 10^{-6\,b}$	10.8	this work
CuBr/TPMA	−0.200	−0.285	−0.243	9.7×10^{-6}	62.4^{c}	38−40
CuBr/Me_6TREN	−0.240	−0.355	−0.298	1.5×10^{-4}	450	38−40

[a] All potentials referred to SCE. [b] Determined by GC. [c] Estimated from the known k_{act} value in the reaction of the complex with 1-phenylethyl bromide.

In that complex, the metal center coordinated five nitrogen atoms with one pyridyl nitrogen not involved in the coordination. Four of the Cu−N bond distances in the present complex were comparable to those in [Cu(TPEN)]$(ClO_4)_2$, but the Cu−N(4) distance in the present compound (represented by the dotted lines in Figure 6) was significantly larger at 2.535(5) Å, indicating a weak interaction between the Cu^{2+} and the N(4) nitrogen atom.

Discussion

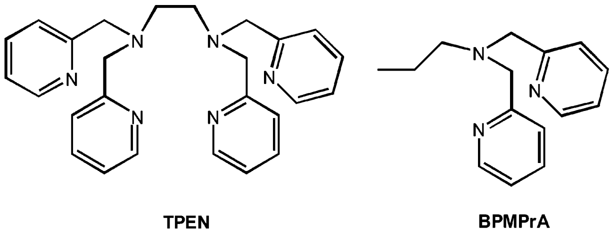
Several recent studies have demonstrated the linear relationship between the K_{ATRP} for many copper-based catalysts and the equilibrium constant K_{ET} of the electron-transfer process from the Cu^{I}/L complex to the Cu^{II}/L complex,[32−34] which is in turn directly related to the redox potential E of the couple $Cu^{II}L/Cu^{I}L$ (eq 2).[35−37] Obviously, a more negative redox potential indicates a larger K_{ATRP} and thus a higher catalytic activity.

$$E \approx -\frac{RT}{F} \ln K_{ET} \qquad (2)$$

where F is the Faraday constant, R is the gas constant, and T is the temperature in Kelvin.

The activity of a given catalyst (in terms of K_{ATRP}) can therefore be predicted from the redox potential of the complex. The measured reduction potential $E_{p,c}$, oxidation potential $E_{p,a}$, and redox potential $E_{1/2}$ of the $Cu^{II}Br_2$/TPEN−Cu^{I}Br/TPEN couple and the $Cu^{II}Br_2$/bis(2-pyridylmethyl)propylamine (BPMPrA)−Cu^{I}Br/BPMPrA couple, these values for the most-used catalysts (CuBr/bipyridine and CuBr/*N*,*N*,*N*′,*N*″,*N*″-pentamethyldiethylenetriamine, PMDETA),[38] and the recently reported highly active catalysts (CuBr/Me_6TREN and CuBr/TPMA) are compared in Table 2.

Scheme 2. Structural Comparison between the Ligand TPEN and BPMPrA



CuBr/TPEN has a K_{ATRP} as high as 2.0×10^{-6}, which is approximately 510, 32, and 27 times greater than those of CuBr/bpy, CuBr/BPMPrA, and CuBr/PMDETA, respectively. Therefore, CuBr/TPEN demonstrated very high catalytic activity in ATRP of MA, MMA, and St even at low catalyst concentrations. TPEN has two sets of the binding unit of BPMPrA: two pyridyl nitrogen atoms and one tertiary amine nitrogen atom (Scheme 2). However, the large differences in catalytic activity (K_{ATRP} and k_{act} in Table 2) between CuBr/TPEN and CuBr/BPMPrA suggested that the real active species of CuBr/TPEN catalyst in solution might not be the binuclear species shown in Figure 5, a simply doubled CuBr/BPMPrA.

^{1}H NMR was used to probe the solution structure of the CuBr/TPEN complex at different CuBr/TPEN ratios. The TPEN ligand in acetone-d_6 had very sharp signals (Figure 7). The binding of CuBr with the TPEN ligand was evidenced from the notable differences in chemical shifts between the complex and the pure ligand. In the 2/1 CuBr/TPEN complex spectrum, the signals corresponding to the pyridine proton py_6 and the β-methylene proton on the ethylene backbone shifted 0.25 ppm (from 8.45 to 8.70) and 0.29 ppm (from 2.76 to 3.05) downfield, respectively, while the py_3 signal shifted upfield from 7.53 to 7.36, close to the py_5 signal. This spectrum is in agreement with that of the reported binuclear Cu^{I} complex $Cu_2(TPEN)(BF_4)_2$,[41] indicating that the CuBr/TPEN at 2/1 molar ratio existed in solution as binuclear complex. On the other hand, the signals of py_6 and the β-methylene proton in CuBr/TPEN at 1/1 molar ratio shifted merely 0.12 and 0.13 ppm downfield and the py_3 resonance shifted only 0.08 ppm upfield. The remarkable broadening of the signals of py_5, py_6, and the methylene proton suggested fast exchanges between different species in the 1/1 CuBr/TPEN complex solution. The ESI-MS spectrum of 1/1 CuBr/TPEN complex solution indicated the existence of both binuclear and mononuclear complex species (Figure 8). The peak at 274.9 amu corresponded to the binuclear species [Cu^{+}(TPEN)Cu^{+}] (calcd 275.1). The peak at 396.0 amu was caused by the in-source fragmentation, which corresponded to the residue from $[Cu(TPEN)]^{+}$ with one picolyl group lost (calcd 396.1). The peak at 486.9 amu was due to the mononuclear species $[Cu(TPEN)]^{+}$ (calcd 487.2), while the peak at 567.6 was [CuBr(TPEN) + H^{+}] (calcd 567.1). Therefore, both mononuclear and binuclear complexes coexisted in the solution of CuBr/TPEN at a 1/1 molar ratio. There was a fast exchange equilibrium between the binuclear and mononuclear complexes, which caused the broadening of the NMR signals in the 1/1

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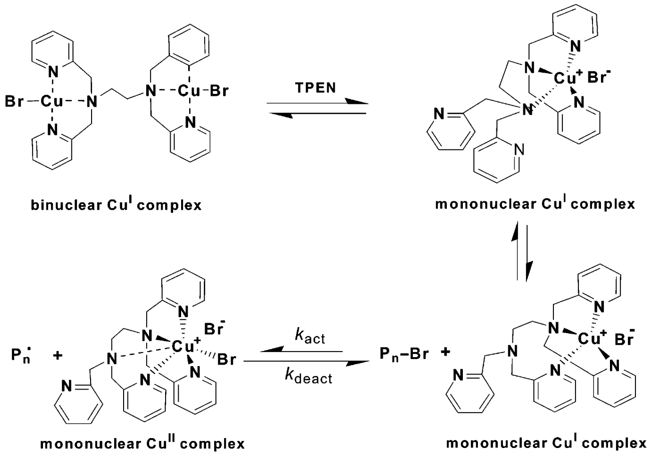
Scheme 3. Equilibrium between the Binuclear and Mononuclear Cu^{I}Br/TPEN Complexes in Solution and the ATRP Equilibrium



CuBr/TPEN spectrum. Since the mononuclear Cu^{I} complex was much more structurally similar to the mononuclear Cu^{II} complex, the structural reorganization from the Cu^{I} mononuclear to the Cu^{II} mononuclear complex was more energy and entropy favorable than from the Cu^{I} binuclear complex to the Cu^{II} mononuclear complex. Indeed, we found that CuBr/TPEN at 1/1 molar ratio had a higher activity than CuBr/TPEN at 2/1. For example, at a Cu/I ratio of 0.01, the polymerization of MA at 1/1 CuBr/TPEN molar ratio reached 65% conversion in 4 h while the polymerization at 2/1 molar ratio could only reach 30% conversion. Thus, the real active species in 1/1 CuBr/TPEN solution was not the binuclear complex but the mononuclear complex. The proposed equilibrium and the ATRP process are sketched in Scheme 3. These mononuclear Cu^{I} complexes were much more reactive because their structures were similar to the Cu^{II} complex, and thus a fast equilibrium between the Cu^{I} and Cu^{II} complexes could be established during the ATRP process.

CuBr/TPMA and CuBr/Me$_6$TREN had higher K_{ATRP} values than CuBr/TPEN (Table 2) and thus were expected to catalyze ATRP of MA, MMA, and St at lower catalyst concentrations. However, both CuBr/TPMA and CuBr/Me$_6$TREN could not mediate successful controlled/"living" polymerizations of MA, MMA, and St at a Cu/I ratio lower than 0.1, in contrast to the fast polymerizations catalyzed by CuBr/TPEN at a Cu/I ratio of 0.005 (Figure 1).

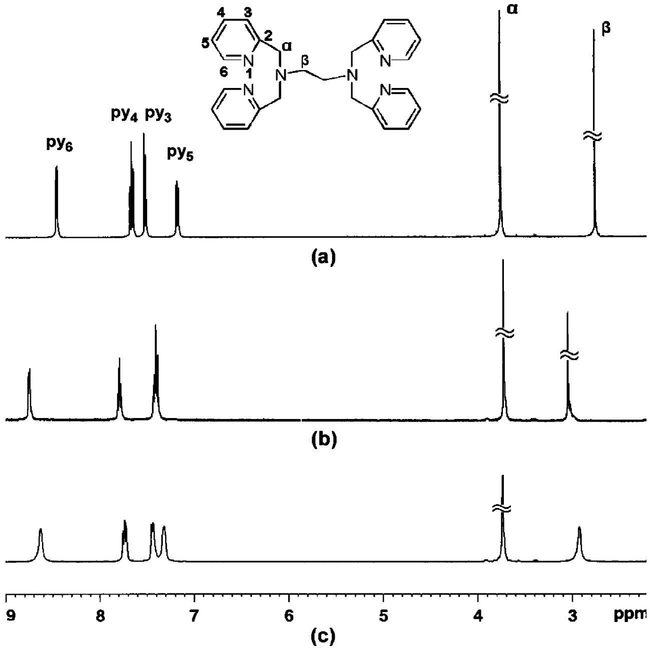


Figure 7. ^{1}H NMR spectra of the TPEN ligand (a) and CuBr/TPEN complex at 2/1 (b) and 1/1 (c) molar ratios in acetone-d_6 at room temperature.

The catalyst stability and K_{ATRP} value may account for the differences. Copper complexes have to be stable in monomer or organic solvents during the polymerization because bare copper ions, Cu^{+} and Cu^{2+}, have almost no catalytic activity. Ligands affect the redox potential of the couple Cu^{II}L/Cu^{I}L through stabilization or destabilization of the Cu^{II} state of the complex. A low redox potential of the Cu^{I}/Cu^{II} is related to the relative stabilization of the Cu^{II} versus the Cu^{I} state upon complexation with the ligand.[42] A ligand forming a more stable Cu^{II} complex will form a more reducing and thus more reactive Cu^{I} complex as an ATRP catalyst.[43] The stability constants of the Cu^{II}Br$_2$/Me$_6$TREN, Cu^{II}Br$_2$/TPMA, and Cu^{II}Br$_2$/TPEN complexes in MA, MMA, and St solutions are not available from the literature, but the reported stability constants in aqueous medium, which can serve as a reference, are 4.5×10^{15}, 1.4×10^{16}, and 3.5×10^{20}, respectively,[44,45] suggesting that Cu^{II}Br$_2$/TPEN is at least 4 orders of magnitude more stable than the other two complexes, and Cu^{II}Br$_2$/Me$_6$TREN is the least stable one of the three complexes. Thus, the reducing power of the Cu^{I} complexes and, consequently, the values of K_{ATRP} should increase in the order Me$_6$TREN < TPMA < TPEN if the stability constants of the corresponding Cu^{I}Br complexes with these three ligands are similar. The quantitative comparison of the stability of the Cu^{I}Br complexes with the three ligands is again unavailable; however, the higher stability of Cu^{II}Br$_2$/TPEN but the less negative redox potential of the Cu^{II}Br$_2$/TPEN−Cu^{I}Br/TPEN couple (Table 2) indicates that Cu^{I}Br/TPEN has a much higher stability constant than Cu^{I}Br/TPMA and Cu^{I}Br/Me$_6$TREN.[36,46] In other words, both the Cu^{I} and Cu^{II} complexes with TPEN ligand are very stable. This is particularly important in designing ATRP catalysts that can mediate polymerizations under high dilution or in coordinating solvents and monomers. It has been reported that monomers such as MA, MMA, and St, alkenes (e.g., 1-octene), and some solvents (e.g., H$_2$O, acetonitrile, and DMF) can coordinate with the copper center.[47−51] Thus, unstable or less stable copper complexes, even though they have very high K_{ATRP} and k_{act}, may dissociate at low catalyst concentrations or change their structures in the coordinating solvents/monomers and therefore lose or reduce their

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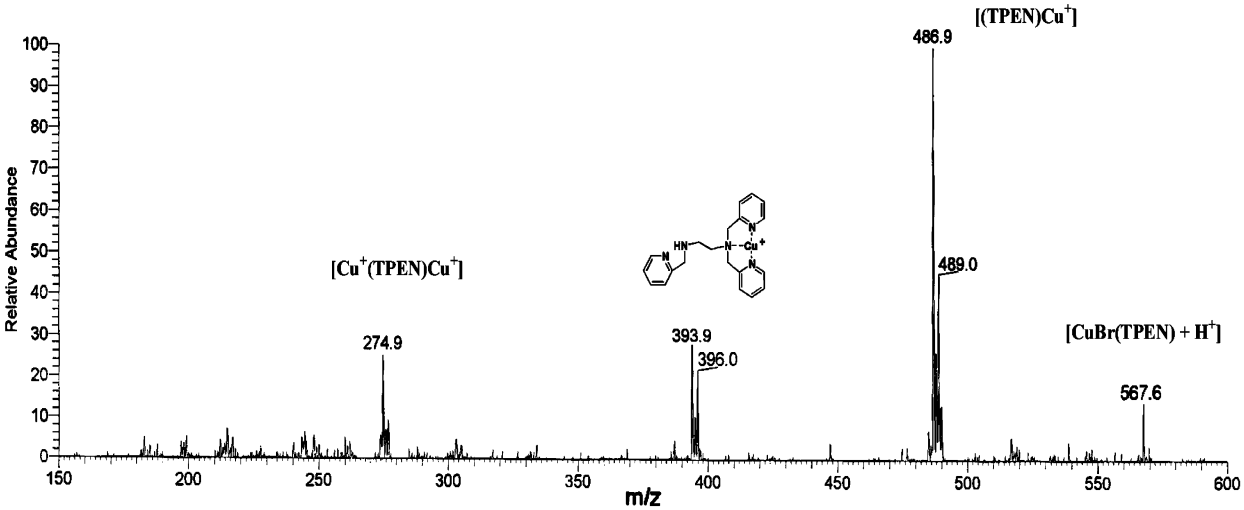

Figure 8. ESI-MS spectrum of the 1/1 CuBr/TPEN complex in acetone.

catalytic activities. This may explain why CuBr/TPMA and CuBr/Me$_6$TREN cannot catalyze controlled polymerizations at low catalyst concentrations even though they have K_{ATRP} and k_{act} constants higher than those of CuBr/TPEN. The catalyst stability should be taken into account in the first place in designing highly active catalysts working under high dilution or in coordinating solvents/monomers.

Another possible reason for the better performance of CuBr/TPEN at low catalyst concentrations may be its slightly lower value of K_{ATRP} than CuBr/Me$_6$TREN and CuBr/TPMA. It has been simulated that during the MMA and St polymerizations, too active catalysts ($K_{\mathrm{ATRP}} > 10^{-5}$) may significantly decrease the polymerization rate, resulting in low final conversion of the polymerization.[30] This is because a too large K_{ATRP} causes too fast activation reaction and thus produces a too high radical concentration at the early stage of the polymerization. This, in turn, causes significant irreversible radical terminations until enough amount of the deactivator is produced to establish the activation/deactivation equilibrium. A considerable amount of initiator and activator is consumed during this process, which substantially decreases the polymerization rate and final conversion. Therefore, for ATRP at low catalyst concentrations, a high K_{ATRP} of the catalyst is necessary but too high K_{ATRP} values could lead to cessation of the polymerization at low monomer conversions. On the other hand, if the catalyst activity is too low (e.g., $K_{\mathrm{ATRP}} < 10^{-8}$, CuBr/bpy in Table 2), the polymerization is slow even at normal catalyst concentration (equimolar to initiator), and such a catalyst cannot be used at low catalyst concentrations. In summary, both high stability and an appropriate K_{ATRP} are crucial for the catalyst working under high dilution or in coordinating solvents/monomers.

Conclusion

A new copper-based complex CuBr/TPEN has been developed as a versatile and highly active catalyst for ATRP of acrylic, methacrylic, and styrenic monomers. This is the first known catalyst that can effectively mediate controlled/“living” radical polymerizations of MA, MMA, and St at CuBr/initiator molar ratio (Cu/I) as low as 0.005 (i.e., catalyst/monomer molar ratio of 5×10^{-5} at a monomer/initiator of 100) and produce polymers with well-controlled molecular weights and low polydispersities. The “living” nature can even be observed in the polymerization at a CuBr/initiator molar ratio of 0.001 with copper concentration in the produced polymers as low as 6−8 ppm (catalyst/monomer molar ratio = 10^{-5}). This is a promising milestone toward a commercial ATRP at industrial scale with catalyst concentration low enough to eliminate the need for post-purification and catalyst recovery. A high stability and an appropriate K_{ATRP} are found to be crucial for the catalyst working under high dilution or in coordinating solvents/monomers. This provides guidance for further design of highly active ATRP catalysts.

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Supporting Information Available: Crystallographic information files (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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