Immobilization of the Copper Catalyst in Atom Transfer Radical Polymerization

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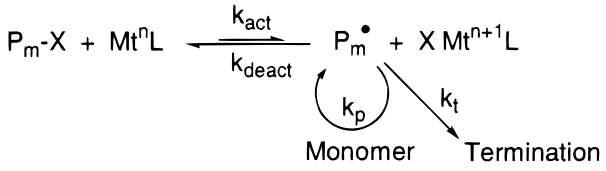
ABSTRACT: Immobilization of the catalyst system for atom transfer radical polymerization (ATRP) on various silica and cross-linked polystyrene supports was studied. The catalyst system comprises a copper halide, complexed by various amines. The effect of size of support particles, the amount of immobilized catalyst, and the addition of Cu(II) species as deactivator in the polymerization were investigated. In all cases, polymerization occurred, but generally the reactions were not as well controlled in terms of molecular weight and polydispersities as homogeneous systems. The molecular weights did not match the predicted values, and polydispersities were high ($1.5 < M_w/M_n < 10$). However, control was improved by either an increase in catalyst concentration or the addition of deactivator still bound to support to the system. Potential reasons for the reduced control could be the low mobility of the supported catalyst and/or the steric hindrance and incompatibilities between the immobilized catalyst and the polymer chain, thus resulting in a less efficient halogen transfer process compared with homogeneous ATRP.

Introduction

Atom transfer radical polymerization (ATRP) is one of the most promising methods in the field of controlled/"living" radical polymerizations.[1] The basis of this technique is the reversible transfer of a halogen atom from a monomeric or polymeric alkyl halide (P_n−X) to a transition metal complex (Mt^nL), forming an organic radical (P_n*) and a transition metal complex with a higher oxidation state ($XMt^{n+1}L$) (Scheme 1).[2−4] The equilibrium between the Mt^nL and $XMt^{n+1}L$ species is strongly shifted toward the Mt^nL complex; hence the concentration of radicals is kept low, termination is reduced, and monomer addition is controlled. Several different catalytic systems can be used for ATRP.[5] In this laboratory, complexes of the Cu(I)/Cu(II) with nitrogen-based multidentate ligand (L) have been preferentially used for the controlled polymerization of a wide range of monomers.[1−3,6,7] However, other transition metals such as Ru,[8] Fe,[9−11] Ni,[12,13] Pd,[14] and Rh[15] have also been employed for ATRP. Many of the polymerizations have been carried out under homogeneous conditions, which often gives better control when compared to heterogeneous catalysts.[3,4,16] This can be primarily attributed to more efficient deactivation of the propagating radicals, which is made possible by sufficiently high concentration of deactivator ($XMt^{n+1}L$).

However, one of the problems of homogeneous ATRP is the removal of the catalyst after the polymerization. The usual procedure for laboratory scale reactions involves precipitation of polymer or filtration of polymer solution through aluminum oxide, which adsorbs the catalyst. These techniques have disadvantages, such as cost, difficulties in scaling up, loss of polymer, and difficulties in separating catalyst from functional polymers that interact with the copper complexes. Other techniques can also be used to remove the catalyst, including treatment with MeOH, Na_2S, or an ion-exchange resin.[17] However, better methods are required for production scale reactions. A possible solution for this predicament is to immobilize the catalytic system on a solid support, thus providing a more efficient way of separating, and potentially recycling, the catalyst.

Scheme 1



The immobilization of metal complexes on silica gel particles, achieved by attaching ligands to the silica surface, has been shown to work quite well for other catalytic systems. In recent literature there are some examples of successful immobilization of catalyst that maintains their activity on a solid support. Some examples include Karstedt's catalyst for the hydrosilylation reaction[18] and a rhenium complex for the epoxidation of alkenes.[19] Solid-supported Ziegler−Natta polymerization catalysts, used for the synthesis of polyolefins, have been known for almost 20 years.[20] After this paper was submitted, Haddleton and co-workers showed that ATRP of methyl methacrylate was feasible using a solid supported Schiff base ligand.[21] New research techniques such as combinatorial chemistry have also led to an increasing demand for supported reaction systems and the development of new immobilized chemical reagents.[22] In this work, we report the use of surface-modified particles with immobilized multidentate nitrogen donor ligands for copper-mediated ATRP.

Experimental Section

Materials. All chemicals were purchased from Aldrich Chemical Co. and used as received, unless otherwise noted. Styrene was passed through an Al_2O_3 column and distilled from CaH_2. Methyl acrylate was extracted three times with 10% NaOH solution and once with H_2O, dried over $MgSO_4$, and distilled from CaH_2. Vinyl acetate was distilled from CaH_2. CuBr was purified by stirring in glacial acetic acid under argon followed by filtration and washing with absolute ethanol. As silica supports, silica gel 5−25 μm (Aldrich), silica powder 0.5 μm (Lancaster), and Aerosil-200V (Degussa) were used. N^1-[3-(Trimethoxysilyl)propyl]diethylenetriamine (Gelest) was used as received. The polymer supported tris(2-aminoethyl)-

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amine (s-TREN, 4.4 mmol of N/g), polymer supported diethylenetriamine (s-DETA, 2.5 mmol of N/g), and Merrifield's peptide resin (1.7 mmol of Cl/g, 1 mol % divinylbenzene cross-linked, 200−400 mesh) were purchased from Aldrich. *N*,*N*-Bis(2-pyridylmethyl)-2-ethylamine (BPMEA) was prepared according to a reported procedure.[23]

General Procedures and Characterizations. ^{1}H NMR spectra were recorded using $CDCl_3$ on a 300 MHz Bruker spectrometer; chemical shifts (δ) are given in ppm relative to TMS. Monomer conversion was determined using a Shimadzu GC14 instrument. Molecular weights and molecular weight distributions were measured using a Waters WISP 710 autosampler and the following PSS GPC columns: guard, 10^5, 10^3, and 10^2 Å. Molecular weights were calibrated using linear polystyrene standards. Thermogravimetric analysis (TGA) was performed on a Rheometric Scientific TGA 1000 with a heating rate of 20 °C/min. Elemental analysis was carried out by Midwest Microlab, Indianapolis, IN. Electrospray ionization (ESI) MS was conducted using a Finnegan LCQ, equipped with an octupole and an ion trap mass analyzer. The atomic absorption spectroscopy was run using Perkin-Elmer atomic absorption spectrometers (model 1100B). Experiments requiring an inert atmosphere were performed using standard Schlenk techniques. Polymerization experiments were carried out in Schlenk flasks or in sealed tubes.

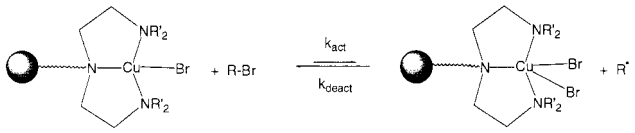
General Procedure of the Coupling of Linear Triamine on a Silica Surface. This reaction was based on a previously published procedure.[24] The silica was heated at 150 °C under vacuum for 24 h before modification. A 10.00 g sample of silica particles was suspended in 80 mL of dry toluene. A 2.00 g (0.034 mol) sample of N^1-[3-(trimethoxysilyl)-propyl]diethylenetriamine was added and the suspension heated under reflux for 48 h. The toluene was removed by evaporation, and the particles were dried at 50 °C under vacuum for 24 h. To further remove residues of the coupling agent, the particles were extracted in a Soxhlet apparatus with MeOH for 24 h and finally dried again at 50 °C under vacuum for 24 h. The amount of ligand immobilized on the surface was determined by TGA and elemental analysis.

Preparation of *N*,*N*-Bis(2-pyridylmethyl)-2-hydroxyethylamine (BPMEA−OH). To a 20 mL of aqueous solution of 4.1 g of 2-picolyl chloride hydrochloride (0.025 mol, 2.0 equiv) was added 0.754 mL of ethanolamine (0.0125 mol, 1.0 equiv). The mixture was stirred and heated to 60 °C. To this solution was added 10 mL of NaOH aqueous solution (2 g, 0.05 mol, 4.0 equiv) was added over 1 h. The dark brown solution was stirred an additional hour and afterward cooled to room temperature. The mixture was extracted with chloroform and concentrated by evaporation of solvent. The dark oil obtained was adsorbed by basic alumina and eluted with chloroform. Concentrating this solution gave the desired product (2.62 g, 86% yield). ^{1}H NMR ($CDCl_3$) δ: 2.86 (t, 2H), 3.67 (t, 2H), 3.92 (s, 4H), 7.13 (dd, 2H), 7.32 (d, 2H), 7.57 (dd,2H), 8.52 (d, 2H). ESI MS ($M + Na^+$): calculated, 266.30; found, 266.2.

Procedure for the Immobilization of *N*,*N*-Bis(2-pyridylmethyl)-2-hydroxyethylamine (BPMEA−OH) on Merrifield Resin. In a glovebox, 0.246 g of BPMEA−OH (1.01 mmol, 5.0 equiv) was dissolved in 10 mL of dry DMF. A 0.0240 g sample of sodium hydride (1.01 mmol, 5.0 equiv) was slowly added to the DMF solution. After stirring for 2 h at room temperature, the mixture was removed from the glovebox. To this solution, 0.119 g of Merrifield resin (0.202 mmol, 1.0 equiv) and 7.5 mg of *n*-Bu_4NI (0.020 mmol, 0.1 equiv) were added sequentially. The mixture was stirred for an additional 48 h at room temperature. The resin was filtered, washed several times with THF, ethyl acetate, methanol, DMF, THF, and ether, and dried overnight under vacuum. Yield (89%) was calculated with nitrogen and chlorine content by elemental analysis.

General Procedure for Polymerization. Monomer, CuBr, $CuBr_2$, the modified particles, and an internal standard for GC measurements were mixed under an argon atmosphere in the ratios shown in the tables. Oxygen was removed from the suspension either by three freeze−pump−thaw cycles or, alternatively, by bubbling argon or nitrogen through the mixture for at least 15 min. The reaction was stirred at 90 or 22 °C for 2 min (unless otherwise noted) to coordinate CuBr and $CuBr_2$ onto the surface of the support. The mixture was allowed to cool, and the initiator was injected.

Scheme 2



General Procedure for Catalyst Removal. (a) Silica-based particles: After dissolving the reaction mixture in THF, it was allowed to stand for at least 30 min during which the particles sank to the bottom of the flask. (b) Cross-linked polystyrene-based particles: After dissolving the reaction mixture in THF, the suspension was filtered through a Gelman Acrodisc 0.20 μm PTFE filter, and the clear solution was obtained for further characterization.

Results and Discussion

The ATRP catalytic system can be immobilized using different methods and/or supports. One of the most efficient methods is binding ligands to silica, while another is the use of cross-linked polymeric beads as support. Linear triamines and TREN were chosen as coordinating ligands for copper bromide because they are commercially available as coupling agents for silica and preformed amines on cross-linked polystyrene. Additionally, linear triamine-coordinated copper compounds have proven to be effective catalysts in ATRP[7] and therefore are good reagents to evaluate the efficiency of the heterogeneous catalysts. While the mechanism of ATRP with triamines as a ligand is not yet known in detail, it seems to be based on the equilibrium reaction described in Scheme 1. On the basis of crystal structures of related complexes,[25,26] the mechanism shown in Scheme 2 is postulated for the supported catalyst. While in previous reports of ATRP with linear amines methylated analogues were used as they gave better control of the polymerization when compared to the hydrogen-substituted species, our first screening of the supported catalysts used the commercially available unmethylated amines. Thus, differences in control in the present systems compared to the methylated triamines may be partially related to the differences in the ligand structures.

Silica Supported Catalyst. The modification of silica surfaces by attachment of silicon alkoxides is a common technique to chemically bind different substrates to surfaces.[24,27,28] The reaction takes place between silanol groups on the surface of the particle and the silicon alkoxides of the substrate, leading to elimination of an alcohol and condensation of the coupling agent onto the surface (Scheme 3). The amount of coupling agent attached to the surface depends on the number of surface OH groups available, the activity of the alkoxide, and the reaction time. Ideally, a fully covered surface was targeted, but only a fraction of the OH groups may react with the alkoxides. For ATRP complete coverage is not necessary; therefore, the condensation reaction was limited to 48 h.

Surface modifications using N^1-[3-(trimethoxysilyl)-propyl]diethylenetriamine were applied to three different supports to compare their activity in ATRP: (a) silica gel with a size distribution between 5 and 25 μm and pore radius of 60 Å, (b) silica powder with a very narrow size distribution in the range of 0.5 μm, and (c) fumed silica, also known under the trademark Aerosil

Scheme 3

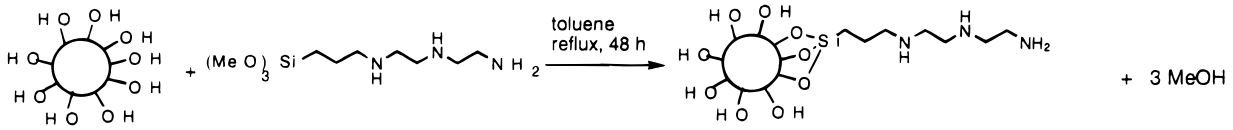
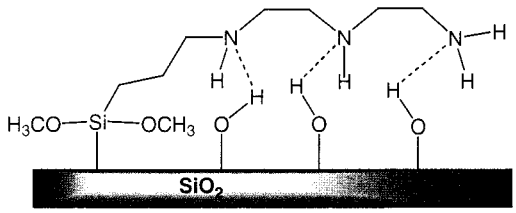


Table 1. Results from TGA and Elemental Analysis for the Attachment of the Triamine to the Surface (All Values in mmol/g)

support	TGA measurement	elemental analysis[a]
silica gel 5−25 μm	0.59	0.60
silica powder	0.25	0.20
Aerosil	0.50	0.49

[a] The molar ratio was calculated by the amount of nitrogen found in the samples.

Scheme 4



200V from Degussa with an average particle size 12 nm and a nonporous structure. The amount of ligand on the surfaces was determined by TGA and elemental analysis. TGA measurements were carried out by heating the particles from room temperature to 800 °C and detecting the percent weight loss, which allowed for the determination of the amount of organic material on the surface. Both techniques gave nearly the same values, with exception of the silica powder sample, where a 20% difference between the two results was obtained (Table 1). The major origin of error in the measurements could be an incomplete condensation reaction leading to the loss of adsorbed coupling agent. For stoichiometric calculations, the result from the elemental analysis was taken. The information based on this method of analysis reflects the differences in the porous structure of the supports. The silica gel is very porous and therefore has a larger surface area which allowed for the condensation of more coupling agent during the same time as in the case of the rather dense silica powder. Aerosil particles are rather small, and the surface area (200 m^2/g) is larger as in the case of the silica powder. Another effect that should be mentioned is the potential back-bonding of the amine protons from attached ligand to surface OH groups, which could also block free hydroxide groups on the surface for further reactions and reduce the catalytic activity (Scheme 4).[29]

The bulk polymerization was carried out with styrene as the monomer and 1-phenylethyl bromide as the initiator. The results for the different supports are shown in Tables 2−4. In most cases an increase in the viscosity of the reaction mixture was observed after a couple of hours at 90 °C. The molecular weight analysis for all reactions showed much higher molecular weights than predicted based on quantitative initiation ($DP_n = \Delta[M]/[I]_0$), and polydispersities were high ($M_w/M_n > 2$).

The silica gel support was used in optimization studies for the polymerizations. One main factor in all reactions seems to be the amount of particles present in the system. An increase in the particle concentration led to a decrease in the ratio between the theoretical and observed molecular weights, as well as a decrease in the polydispersities. In the cases with the silica gel particles (Table 2) and the Aerosil (Table 4), molecular weights were about 50% higher than the theoretical ones, which may be explained by propagation being faster than initiation or by slow deactivation, both resulting in incomplete initiation. Improvement of the deactivation rate was attempted by the addition of Cu(II)Br_2 to the reaction solution, but no reduction in the polydispersities was observed (entry 2 in Table 2).

Table 2. Results of Bulk Polymerization of Styrene Using Silica Gel 5−25 μm Supported Ligand at 90 °C, Ar

no.	$[M]_0/[I]_0/[CuBr]_0/[L]_0$[a]	time [min]	conv [%]	$M_n \times 10^3$	M_n(th) $\times 10^3$	M_w/M_n
1	96/1/1/1/1	368	50.9	21.6	5.1	5.66
2	96/1/1/1/1 + 0.1 $CuBr_2$	363	58.0	17.6	5.8	7.17
3	480/1/2/2	352	22.8	50.2	11.4	4.02
4	960/1/1/4	344	40.0	66.5	40.0	3.61
5	960/1/1/8	347	41.1	66.3	41.1	3.07
6	960/1/4/4	1160	55.1	111.2	55.1	3.07
7	960/1/8/8	1160	49.1	102.1	49.1	2.69
8	96/1/1/1[b]	263	26.5	4.8	2.6	2.18
9	960/1/8/0[c]	446	7.0	6.7	7.0	2.72

[a] $[M]_0/[I]_0/[CuBr]_0/[L]_0$ = [styrene]$_0$/[1-phenylethyl bromide]$_0$/[CuBr]$_0$/[silica gel supported ligand]$_0$. [b] Polymerization with unattached ligand *N′*-[3-(trimethoxysilyl)propyl]diethylenetriamine. [c] Polymerization experiment with unmodified silica particles.

Table 3. Results of Bulk Polymerization of Styrene Using Silica Powder Supported Ligand, 90 °C, Ar

no.	$[M]_0/[I]_0/[CuBr]_0/[L]_0$[a]	time [min]	conv [%]	$M_n \times 10^3$	M_n(th) $\times 10^3$	M_w/M_n
1	480/1/1/1	1124	30.5	9.7	15.3	7.96
2	480/1/2/2	1234	62.8	19.5	31.4	5.62
3	480/1/4/4	1235	73.4	15.2	36.7	6.48

[a] $[M]_0/[I]_0/[CuBr]_0/[L]_0$ = [styrene]$_0$/[1-phenylethyl bromide]$_0$/[CuBr]$_0$/[silica powder supported ligand]$_0$.

Table 4. Results of Bulk Polymerization of Styrene Using Aerosil Supported Ligand, 90 °C, Ar

no.	$[M]_0/[I]_0/[CuBr]_0/[L]_0$[a]	time [min]	conv [%]	$M_n \times 10^3$	M_n(th) $\times 10^3$	M_w/M_n
1	480/1/1/1	296	48.4	11.2	24.2	8.88
2	480/1/2/2	279	37.8	13.7	18.9	5.95
3	480/1/4/4	1234	37.6	18.9	18.8	4.76
4	480/1/8/8[b]	125	13.7	10.9	6.9	9.92

[a] $[M]_0/[I]_0/[CuBr]_0/[L]_0$ = [styrene]$_0$/[1-phenylethyl bromide]$_0$/[CuBr]$_0$/[Aerosil supported ligand]$_0$. [b] Very viscous system, insufficient stirring.

Entry 8 in Table 2 shows that polymerization with *N′*-[3-(trimethoxysilyl)propyl]diethylenetriamine as the ligand for the active copper species produced better control of molecular weights and molecular weight distribution than for the immobilized catalysts. However, it also showed higher molecular weights than the expected value and higher polydispersities than those reported for the methylated linear triamines.[7] As a further comparison, the behavior of unmodified silica particles in ATRP was determined (entry 9 in Table 2).

The typical evolution of molecular weights with conversion for the styrene bulk polymerization using the

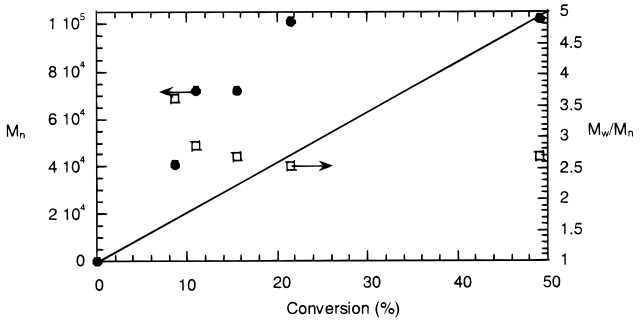


Figure 1. Molecular weight evolution with conversion for styrene bulk polymerization with silica gel 5−25 μm supported catalyst, 1-phenylethyl bromide as initiator, $[M]_0/[I]_0/[CuBr]_0/[L]_0$: 960/1/8/8, T = 90 °C, argon.

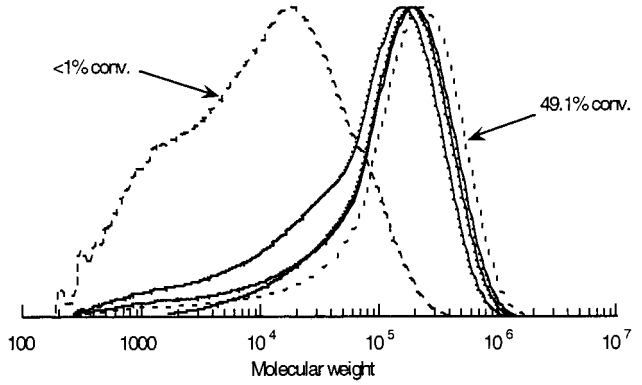
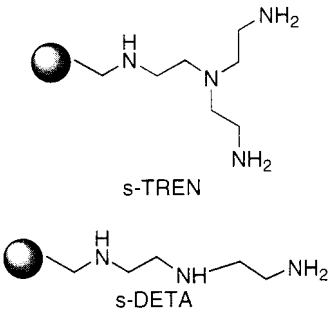


Figure 2. GPC mass distribution for styrene bulk polymerization with silica gel 5−25 μm supported catalyst, and 1-phenylethyl bromide as initiator, $[M]_0/[I]_0/[CuBr]_0/[L]_0$: 960/1/8/8, T = 90 °C, Ar. Conversion increases for curves from left to right; <1% sample was taken before raising temperature to 90 °C.

catalyst supported on 5−25 μm silica is shown in Figure 1. Molecular weights were higher than the theoretical values calculated assuming quantitative initiation, but they increased up to 20% conversion. The polydispersities were rather high, slightly decreasing during the reaction. Figure 2 shows the molecular weight distributions from GPC measurements. The curves are normalized, and the molecular weight distribution of the polymer shifted to higher molecular weight with increasing conversion. Each curve, however, has a long tail at low molecular weight, which is contributing significantly to the high polydispersities. This tail is probably caused by uncontrolled polymerization, which occurs at the early stage of the reaction when not enough CuX_2 is present, leading to insufficient deactivation of the growing radicals.

Silica Powder. The silica powder was used to examine the influence of particle size on the reaction. The particles obtained from Lancaster have a diameter of 0.5 μm with a low dispersity of particle size. Modification with the silicon alkoxide led to a much lower amount of ligand on the surface relative to the silica gel or the Aerosil. The lower loading originates in the nonporous structure of the silica powder, which has a much smaller surface area and therefore does not allow the same degree of modification as the porous materials. In contrast to the silica gel, the powder showed another trend concerning molecular weights. In this case, the observed molecular weights were always lower than the theoretical ones, with high polydispersities (Table 3). Lower molecular weights than theoretical values originate from an unidentified transfer reaction.

Scheme 5



Aerosil. Aerosil is the brand name of Degussa's fumed silica. The average particle size of this material is very small (12 nm), and it has a very large surface area (200 m^2/g). This material was modified with ligand using the same method as in the previous two surface modifications. The amount of ligand immobilized was smaller compared with the silica gel supports. Table 4 shows that molecular weights in the polymerizations were closer to the theoretical ones, and polydispersities showed the same dependence on the amount of particles used as in the case of silica gel. The difficulty using Aerosils was that the solution became very viscous in all cases and viscosity increased with increase of particle concentration, which is a well-known phenomenon of this silica species. Therefore, the mobility of the particles, and at the same time the catalyst, could only be maintained by vigorous stirring such that the particle agglomerates were broken. At high concentration of Aerosil, in the reaction mixture stirring was nearly impossible.

Organic Polymer Supported Ligands. The organic polymer-supported ligands are based on linear triamines or tetramines, immobilized on cross-linked polystyrene Merrifield resin (Scheme 5). These systems are commercially available and are used as a quenching reagent in combinatorial chemistry.[30] The resin used for immobilization here had a small size (200−400 mesh for s-TREN) and low cross-linking density (1 or 2% divinylbenzene for s-DETA and s-TREN, respectively).[31] On the basis of the polymeric nature of the support, the systems should exhibit high compatibility between the support and the growing chains. They also show a high loading of functional groups (1.2−1.5 mmol/g). One disadvantage of these particles was their swelling behavior due to their cross-linked nature, which led to limited mobility, as similarly observed for the Aerosil support.

With these supports, several polymerizations with various monomers were carried out (Tables 5 and 6). The polymer supported tris(2-aminoethyl)amine (s-TREN) showed the best results for methyl acrylate (MA) polymerizations. In the case of styrene (St) and methyl methacrylate (MMA), the polydispersities were higher, and the polymerizations were slower when compared to the case of methyl acrylate. Vinyl acetate did not polymerize under the given conditions (Table 5). Using the polymer supported diethylenetriamine (s-DETA) system, the polymerization of MA was fast and the polydispersity was high (Table 6).

Tailored Polymer Supported Ligands. The commercially available ligands described above may not be the best choice for ATRP reactions, as can be deduced from the polymerization using unbound ligand (entry 8 in Table 2). Therefore, new ligands for the immobiliza-

Table 5. Results of Polymerization Using Polymer Supported Tris(2-aminoethyl)amine (s-TREN) with Ethyl 2-Bromopropionate as Initiator

no.	monomer	$[M]_0/[I]_0/[CuBr]_0/[L]_0$	temp [°C]	time [min]	conv [%]	$M_n \times 10^3$	M_n(th) $\times 10^3$	M_w/M_n
1	MA	200/1/1/1[a]	22	220	37.4	4.95	7.48	24
2	MA	200/1/1/1[a]	90	90	60.2	11.7	10.5	3.14
3	MA	200/1/1/1[a]	90	220	76.4	7.48	13.8	3.28
4	St	100/1/1/1[a]	90	420	47.8	5.66	4.78	13.4
5	St	100/1/1/1[a]	110	220	54.9	5.95	5.49	12.2
6	MMA[b]	200/1/1/1[c]	90	120	28.8	3.82	5.76	19.6
7	VA[c]	200/1/1/1[c]	90	420	0			

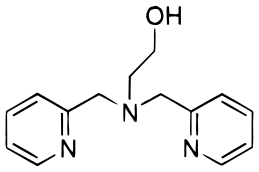
[a] $[M]_0/[I]_0/[CuBr]_0/[L]_0$ = $[monomer]_0/[methyl\ 2\text{-}bromopropionate]_0/[CuBr]_0/[s\text{-}TREN]_0$. [b] 50 vol % anisole solution. [c] $[M]_0/[I]_0/[CuBr]_0/[L]_0$ = $[MMA]_0/[2\text{-}bromopropionitrile]_0/[CuBr]_0/[s\text{-}TREN]_0$.

Table 6. Results of Polymerization Polymer Supported Diethylenetriamine (s-DETA) Used in Bulk Polymerization Reactions with Ethyl 2-Bromopropionate as Initiator

no.	monomer	$[M]_0/[I]_0/[CuBr]_0/[L]_0$	temp [°C]	time [min]	conv [%]	$M_n \times 10^3$	M_n(th) $\times 10^3$	M_w/M_n
1	MA[a]	230/1/1/1[a]	90	8	34.3	24.4	6.88	17.0
2	St	100/1/1/1[a]	90	300	24.0	56.6	2.40	1.98

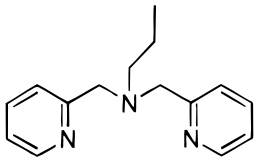
[a] $[M]_0/[I]_0/[CuBr]_0/[L]_0$ = $[monomer]_0/[methyl\ 2\text{-}bromopropionate]_0/[CuBr]_0/[s\text{-}DETA]_0$.

Scheme 6



N,N'-Bis(2-pyridylmethyl) 2-hydroxyethylamine

(BPMEA-OH)



N,N'-Bis(2-pyridylmethyl) ethylamine

(BPMEA)

tion of the catalyst in ATRP need to be developed. Ideally the new ligands for immobilization should provide controlled polymerization under homogeneous conditions and second should contain a functionality to be attached to the polymeric support. To meet these requirements, tridentate ligands with two pyridines and one amine were prepared (Scheme 6). To monitor the effect of the hydroxyl group, an ethyl-substituted ligand was also prepared. These ligands were tested for use in ATRP with different monomers before immobilization (Tables 7 and 8). The two ligands gave better control than the unmethylated amines. Note that the ethyl-substituted ligand resulted in better control, especially for the methyl acrylate polymerization (entry 1 in Table 8).

The BPMEA−OH was immobilized on a commercially available Merrifield resin containing a benzyl chloride functional group, which is used widely for peptide synthesis and combinatorial synthesis of small organic molecules.[22] The Merrifield resin used is based on lightly cross-linked polystyrene (1 mol % divinylbenzene) with a small size (200−400 mesh) and high loading density (1.7 mmol/g). Since methyl acrylate (MA) provided the best-controlled polymerization using BPMEA and BPMEA−OH before immobilization, the following study was continued using methyl acrylate as a monomer. In the first experiment (entry 1 in Table 9), a bimodal molecular weight distribution was observed by GPC (Figure 3a). The reason for the bimodal molecular weight distribution is not clear, but it is likely that initially the growing radicals cannot easily access the deactivator and thus polymerize in an uncontrolled

Table 7. Results of Polymerization Using BPMEA−OH as Ligand

monomer	$[M]_0/[I]_0/[CuBr]_0/[L]_0$	temp [°C]	time [min]	conv [%]	$M_n \times 10^3$	M_n(th) $\times 10^3$	PDI
MA[a]	230/1/1/1[b]	22	120				
		90	170	80.4	15.9	16.8	1.41
St[a]	98/1/1/1[b]	22	120				
		90	170	47.6	6.1	4.8	1.71
MMA[c]	199/1/1/1[d]	22	280	27.9	8.0	5.6	1.74

[a] Reaction was stirred at 22 °C for 2 h and then heated at 90 °C. [b] $[M]_0/[I]_0/[CuBr]_0/[L]_0$ = $[monomer]_0/[methyl\ 2\text{-}bromopropionate]_0/[CuBr]_0/[BPMEA{-}OH]_0$. [c] 50 vol % anisole solution. [d] $[M]_0/[I]_0/[CuBr]_0/[L]_0$ = $[monomer]_0/[2\text{-}bromopropionitrile]_0/[CuBr]_0/[BPMEA{-}OH]_0$.

Table 8. Results of Polymerization Using BPMEA as Ligand

no.	monomer	$[M]_0/[I]_0/[CuBr]_0/[L]_0$	temp[a] [°C]	time[a] [min]	conv [%]	$M_n \times 10^3$	M_n(th) $\times 10^3$	M_w/M_n
1	MA	230/1/1/1[b]	22	40				
			90	25	85.9	18.3	17.2	1.10
2	St	98/1/1/1[b]	22	40				
			90	130	67.0	9.8	6.7	1.36
3	MMA[c]	199/1/1/1[d]	22	40				
			90	130	53.9	18.3	10.8	1.71

[a] All reaction was stirred at 22 °C for 40 min and then heated at 90 °C. [b] $[M]_0/[I]_0/[CuBr]_0/[L]_0$ = $[monomer]_0/[methyl\ 2\text{-}bromopropionate]_0/[CuBr]_0/[BPMEA]_0$. [c] 50 vol % anisole solution. [d] $[M]_0/[I]_0/[CuBr]_0/[L]_0$ = $[monomer]_0/[2\text{-}bromopropionitrile]_0/[CuBr]_0/[BPMEA]_0$.

Table 9. Results of Polymerization Using s-BPMEA Carried out under Different Conditions

no.	monomer	$[M]_0/[I]_0/[CuBr]_0/[CuBr_2]_0/[L]_0$	temp[a] [°C]	time[a] [min]	conv [%]	$M_n \times 10^3$	M_n(th) $\times 10^3$	M_w/M_n
1	MA	230/1/1/0/1[b]	22	180	31.9	10.2	6.4	57.4[c]
2	MA	230/1/0.75/0.25/1[b]	22	180				
			90	60	50.3	40.8	10.6	2.68
3	MA	230/1/0.50/0.50/1[b]	22	180				
			90	180	62.3	36.7	12.5	1.90
4	MA	230/1/0.25/0.75/1[b]	22	40				
			90	930	67.1	26.7	13.4	1.62
5	MA	230/1/0.25/0.75/1[b]	22	40				
			90	930	79.4	18.0	15.9	1.69
6	MMA[d]	203/1/0.50/0.50/1[e]	22	180				
			90	900	68.4	23.9	13.7	1.92
7	St	192/1/0.50/0.50/1[b]	22	180				
			90	900	65.7	30.0	13.1	2.14

[a] Reaction was stirred at 22 °C for 3 h and then heated at 90 °C. [b] $[M]_0/[I]_0/[CuBr]_0/[CuBr_2]_0/[L]_0$= [monomer]$_0$/[methyl 2-bromopropionate]$_0$/$[CuBr]_0/[CuBr_2]_0$/[s-BPMEA]$_0$. [c] Bimodal distribution. [d] 50 vol % anisole solution. [e] $[M]_0/[I]_0/[CuBr]_0/[CuBr_2]_0/[L]_0$ = [monomer]$_0$/[2-bromopropionitrile]$_0$/$[CuBr]_0/[CuBr_2]_0$/[s-BPMEA]$_0$.

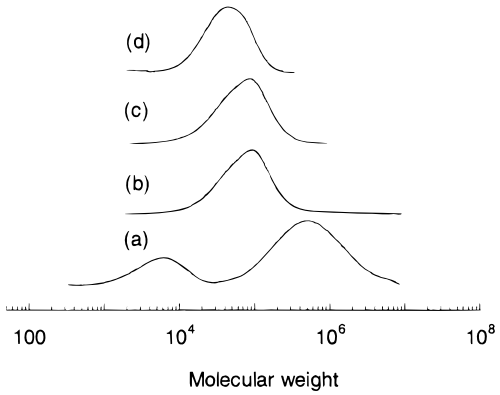


Figure 3. GPC mass distribution for methyl acrylate bulk polymerization with s-BPMEA, methyl 2-bromopropionate as initiator with different ratios of $Cu(II)Br_2$ to Cu(I)Br, $T = 90$ °C, N_2. (a) $[M]_0/[I]_0/[CuBr]_0/[Cu(II)Br_2]_0/[L]_0$: 230/1/1/0/1. (b) $[M]_0/[I]_0/[Cu(I)Br]_0/[Cu(II)Br_2]_0/[L]_0$: 230/1/0.75/0.25/1. (c) $[M]_0/[I]_0/[Cu(I)Br]_0/[Cu(II)Br_2]_0/[L]_0$: 230/1/0.5/0.5/1. (d) $[M]_0/[I]_0/[Cu(I)Br]_0/[Cu(II)Br_2]_0/[L]_0$: 230/1/0.25/0.75/1.

manner resulting in the high molecular peak. After generation of enough deactivator by irreversible termination, controlled polymerization then proceeds (low molecular peak). To enhance the deactivation process, a deactivator, $Cu(II)Br_2$ together with activator Cu(I)Br, was added at the beginning of the reaction. The total amount of copper species was kept to an equimolar amount of the solid supported ligand; therefore, all the copper species should be complexed by solid supported ligand. Three different ratios of $Cu(II)Br_2$ to Cu(I)Br were tested. With larger amounts of $Cu(II)Br_2$, the molecular weights were closer to the expected values with lower polydispersity (Figure 3b−d and entries 2−5 in Table 9). These observations suggest that the larger amount of $Cu(II)Br_2$ leads to an increase in the rate of deactivation, thus improving control.

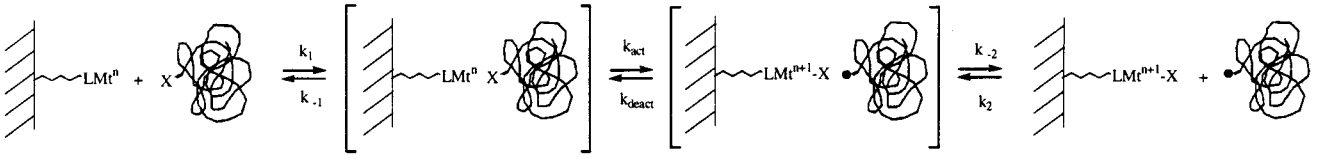
After polymerization, the reaction mixture was diluted in THF, and the filtration of the mixture provided an optically clear solution. The amount of copper in that solution was determined by UV and atomic absorption (AA) for one sample (entry 5 in Table 9). From UV, no detectable amount of copper(II) species was observed. The atomic absorption experiment detected about 5 ppm of copper in the THF solution, which is about 3% of initial amount of total copper. After washing the solid supported catalyst with methanol, the amount of copper in methanol was below 1 ppm, determined again by AA. This indicates that the copper was actually bound to the resin.

As in other heterogeneous systems, the reproducibility is thought to be dependent on the various factors such as the rate of stirring, reactor design, etc. However, entries 4 and 5 of Table 9 show that the reproducibility in these experiment is reasonable.

Conditions for the polymerization of MMA and Sty were similar to that of MA. With equimolar amounts of $Cu(II)Br_2$ and Cu(I)Br, the results were also similar to MA (entries 6 and 7 in Table 9). The molecular weights were approximately twice larger than expected, and the M_w/M_n values were around 2.0, still higher than under homogeneous conditions but lower than the previous examples of solid supported catalyst presented here.

Both the mobility of the particles carrying the immobilized catalyst and the diffusion of the polymer coils in the reaction mixture can affect the control in ATRP. The catalyst is attached to a bulky support that hinders the diffusion of the growing chain end to the catalytic site (Scheme 7). In homogeneous ATRP, the rate constant of activation in ATRP is typically in the range of $k_{act} \approx 10^0$ L mol^{-1} s^{-1} and that of deactivation $k_{deact} \approx 10^7$ L mol^{-1} s^{-1}.[4,32] Diffusion of the active and dormant chain ends to the activator and deactivator immobilized on the surface may be in the range of microseconds or milliseconds. Therefore, the overall rate of activation should not be affected significantly ($k_1 \gg k_{act}$). However, the overall rate of deactivation may be significantly slower than with a homogeneous catalyst, and diffusion may become rate-determining ($k_2 \ll k_{deact}$). This results in poor control due to slow deactivation and requires a higher concentration of the deactivator than under homogeneous conditions. This can explain why a large excess of Cu(II) is needed for control and also why

Scheme 7



polymerization occurs despite the enormous excess of Cu(II), in contrast to homogeneous systems.

The deactivation rate could be enhanced by the addition of deactivator at the beginning of the polymerization. Increasing the initial concentration of deactivator enhances the probability that growing radicals will react with it and be transformed to the dormant species. Also, an increase in the number of particles increased the number of catalyst sites in the mixture and caused a higher probability of deactivation in the polymerization. Further improvements are being pursued: (i) better ligand design, (ii) use of longer spacers between the support surface and the catalytic center to increase the flexibility of the catalyst approaching the polymer chain end, thus improving the "homogeneity" of the catalysts, and (iii) increasing the mobility of the catalytic species by applying smaller supports and more efficient mixing.

Conclusions

It is possible to carry out ATRP with catalysts immobilized on supports. These supports can be organic or inorganic materials. The reactions showed that the abstraction of halogen atoms from the chain end is successful, but deactivation of the growing radical was slow. Improvements in the degree of control were possible by increasing the catalytic site concentration and externally increased deactivator concentration.

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References and Notes

(1) Matyjaszewski, K., Ed. *Controlled Radical Polymerization;* ACS Symp. Ser. Vol. 685; American Chemical Society: Washington, DC, 1998.
(2) Matyjaszewski, K.; Wang, J.-S. *Macromolecules* **1995**, *28*, 7901.
(3) Matyjaszewski, K.; Patten, T. E.; Xia, J.; Abernathy, T. *Science* **1996**, *272*, 866.
(4) Matyjaszewski, K.; Patten, T. E.; Xia, J. *J. Am. Chem. Soc.* **1997**, *119*, 9, 674.
(5) Qiu, J.; Matyjaszewski, K. *Acta Polym.* **1997**, *48*, 169.
(6) Xia, J.; Gaynor, S. G.; Matyjaszewski, K. *Macromolecules* **1998**, *31*, 5958.
(7) Xia, J.; Matyjaszewski, K. *Macromolecules* **1997**, *30*, 7697.
(8) Kato, M.; Kamigaito, M.; Sawamoto, M.; Higashimura, T. *Macromolecules* **1995**, *28*, 1721.
(9) Ando, T.; Kamigaito, M.; Sawamoto, M. *Macromolecules* **1997**, *30*, 4507.
(10) Matyjaszewski, K.; Wei, M.; Xia, J.; McDermott, N. E. *Macromolecules* **1997**, *30*, 8161.
(11) Moineau, G.; Dubois, P.; Jerome, R.; Senninger, T.; Teyssie, P. *Macromolecules* **1998**, *31*, 545.
(12) Granel, C.; Dubois, P.; Jerome, R.; Teyssie, P. *Macromolecules* **1996**, *29*, 8576.
(13) Uegaki, H.; Kotani, Y.; Kamigaito, M.; Sawamoto, M. *Macromolecules* **1997**, *30*, 2249.
(14) Lecomte, P.; Drapier, I.; Dubois, P.; Teyssie, P.; Jerome, R. *Macromolecules* **1997**, *30*, 7631.
(15) Moineau, G.; Granel, C.; Dubois, P.; Jerome, R.; Teyssie, P. *Macromolecules* **1998**, *31*, 542.
(16) Percec, V.; Barboiu, B.; Neumann, A.; Ronda, J. C.; Zhao, M. *Macromolecules* **1996**, *29*, 3665.
(17) Matyjaszewski, K.; Gaynor, S. G.; Teodorescu, S. M. US Patent Pending.
(18) Brook, M. A.; Ketelson, H. A.; LaRonde, F. J.; Pelton, R. *Inorg. Chim. Acta* **1997**, *264*, 125.
(19) Wang, T.-J.; Li, D.-C.; Bai, J.-H.; Huang, M.-Y.; Jiang, Y.-Y. *J. Macromol. Sci., Pure Appl. Chem.* **1998**, *A35*, 531.
(20) Zakharov, V. A.; Yermakov, Y. A. *Catal. Rev.—Sci. Eng.* **1997**, *19*.
(21) Haddleton, D. M.; Kukulj, D.; Radigue, A. P. *Chem. Commun.* **1999**, 99.
(22) Jung, G., Ed. *Combinatorial Peptide and Nonpeptide Libraries*; VCH Verlagsgesellschaft: Weinheim, 1996.
(23) Pal, S.; Chan, M. K.; Amstrong, W. H. *J. Am. Chem. Soc.* **1992**, *114*, 6398.
(24) Hoorn, H. J.; Joode, P. d.; Dijkstra, D. J.; Driessen, W. L.; Kooijman, H.; Veldman, N.; Spek, A. L.; Reedijk, J. *J. Mater. Chem.* **1997**, *7*, 1747.
(25) Boeyens, J. C. A.; Dobson, S. M.; Mboweni, R. C. M. *Acta Crystallogr., Sect. C* **1991**, *47*, 186.
(26) Breeze, S. R.; Wang, S. *Inorg. Chem.* **1996**, *35*, 3404.
(27) Arkles, B. *CHEMTECH* **1977**, *7*, 766.
(28) Ulman, A. *Adv. Mater.* **1990**, *2*, 573.
(29) Vandenberg, E. T.; Bertilsson, L.; Liedberg, B.; Uvdal, K.; Erlandsson, R.; Elwing, H.; Lundtroem, I. *J. Colloid Interface Sci.* **1991**, *147*, 103.
(30) Booth, R. J.; Hodges, J. C. *J. Am. Chem. Soc.* **1997**, *119*, 4882.
(31) Information provided by Aldrich Chemical Co.
(32) Ohno, K.; Goto, A.; Fukuda, T.; Xia, J.; Matyjaszewski, K. *Macromolecules* **1998**, *31*, 2699.

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