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Copper(I)-Mediated Living Radical Polymerization under Fluorous Biphasic Conditions

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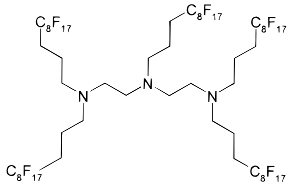
Transition metal-mediated living radical polymerization of vinyl monomers has been introduced as versatile chemistry enabling the synthesis of a wide range of addition polymers with controlled molar mass, molar mass distribution (MMD), end group(s), and topology.[1] This approach has been developed as an extension to atom-transfer radical addition,[2] in particular atom-transfer radical cyclizations of α,α,α-trichlorinated carbonyl compounds.[3] A number of effective living polymerization systems have been reported with a range of transition metal complexes/ligands including RuCl$_2$(PPh$_3$)$_3$;[4] copper(I) in association with bipyridine ligands,[5] multidentate aliphatic amines,[6] and pyridine imines;[7] Ni(II);[8] Rh(III);[9] and Pd(0).[10] These systems have been applied to a wide range of monomers[11] including many different functional monomers.[12] The main attraction of this chemistry is its robust character and its tolerance to most functional groups present in reagents, solvents, and impurities,[13] precluding the extensive use of protecting group chemistry and laborious reagent and solvent purification. This has enabled an impressive array of novel polymers to be synthesized. For example, star polymers based on calixarene, carbohydrate, metallo-organic, and other simple cores;[14] block copolymers from both sequential addition and from macroinitiators;[15] end-functional polymers;[16] polymer brushes;[17] and glycopolymers[18] have all been reported.

Copper-mediated atom-transfer polymerization of (meth)-acrylates is usually carried out in organic solvents such as toluene[7b] or aromatic ethers,[19] depending upon the catalyst system. The rate of polymerization can be enhanced by the presence of certain polar impurities,[20] by the use of aliphatic multidentate tertiary amines,[6] or in aqueous media,[21] which can allow the reaction to be carried out even at ambient temperatures or with reduced catalyst concentration by changing the nature of the active catalyst present during polymerization. To reduce the metal contamination of products and in an attempt to reuse the catalyst, insoluble supports have been used, whereby copper(I) has been bound to covalently attached pyridine imine ligands on both cross-linked poly(styrene) resin and aminated silica gel as well as supported aliphatic amines.[22]

Fluorous biphase chemistry has been developed as a liquid−liquid biphasic process whereby the two phases become miscible under the reaction conditions.[23] This allows the facile separation of product from the catalyst under ambient conditions. This technique relies on catalysts, which are rendered soluble in fluorinated solvents by the use of fluorinated ligands whereby the electronic effects of the fluorine are isolated from the metal center. This approach has been used for a range of diverse processes such as oxidation,[24] aromatic coupling,[25] hydroformylation,[23a] and epoxidation.[26] Very recently, fluorous biphasic catalysis has been used in the Kharash addition of CCl$_4$ to methyl methacrylate[27] and in copper(I)-mediated cyclization of unsaturated esters,[3a] reactions closely related to transition metal-mediated living radical polymerization. These observations prompted us to investigate the use of the fluorous biphase as a medium for atom-transfer polymerization that would allow for the recovery of catalyst-free product and for reuse of catalyst. This communication reports our initial findings.

The addition of pentakis-*N*-(4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,11-heptadecafluoroundecyl)-1,4,7-triazaheptane (**1**)[3a] to a suspension of Cu^{I}Br, at ambient temperature under nitrogen, in perfluoromethyl cyclohexane results in a dark green solution which is immiscible with an equivolume amount of toluene. Only a faint coloration is observed in the hydrocarbon layer. Addition of methyl methacrylate (20% v/v) and ethyl 2-bromoisobutyrate (**2**) as polymerization initiator results in efficient polymerization with 76% conversion to polymer in 300 min at 90 °C, with M_n = 11 100 (theoretical M_n, assuming a living polymerization, at this conversion, of 7600) and a molar mass distribution of 1.30 (Figure 1). The low efficiency of the initiator (68%) is ascribed to loss of initiator at the early stages of the reaction due to coupling of



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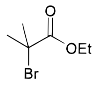

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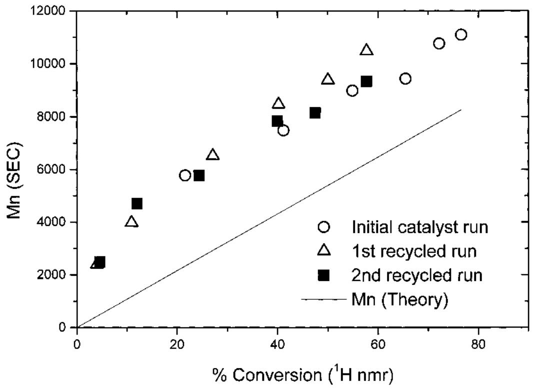

Figure 1. Evolution of M_n with conversion for the fluorous biphase polymerization of MMA initial run and two subsequent catalyst recycles; line drawn represents the predicted M_n based on **2** as initiator where $M_{n,theor} = ([MMA]/[\mathbf{2}])M_{r(MMA)} \times$ % conversion.

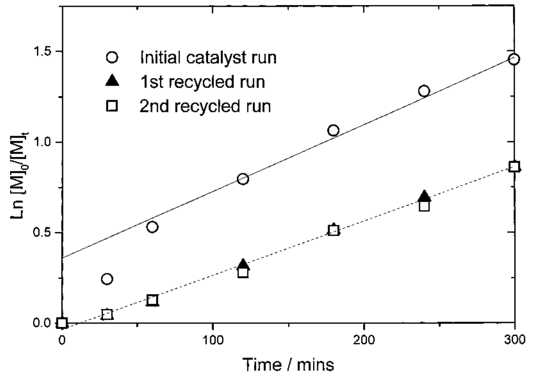

Figure 2. First-order kinetic plots for the fluorous biphase polymerization of MMA; regression lines were drawn through the last four points of the initial run and first recycle so as to allow a comparison of rates of polymerization.

low-mass radicals, as has been observed previously with this type of initiator.[7b] Although the reaction mixture becomes dark green with efficient stirring, it is apparent that under these conditions the system does *not* become monophasic. The M_n increases reasonably linearly with conversion (Figure 1), following a trend consistently higher than that observed with the theoretical M_n; this is similar to the observation with atom-transfer polymerization of MMA under these conditions in hydrocarbon solution.[7b] A first-order kinetic plot (Figure 2) shows a decrease in the rate of polymerization over the first 2 h prior to a constant rate being reached. After polymerization, the reaction was cooled to ambient temperature and the two phases re-formed, a dark green lower layer and a colorless upper layer. After separation of the upper hydrocarbon layer, washing of the fluorous layer with toluene, and subsequent removal of volatiles, PMMA was obtained as a colorless glassy solid. ICP analysis of the product showed a copper level of 0.088% as opposed to 1.5%, which would be expected if all of the catalyst remained in the polymer. A second shot of degassed monomer, toluene, and **2** was added to the green fluorous phase from the initial reaction and the mixture reheated to 90 °C for 300 min. Efficient polymerization ensued, giving PMMA in 58% yield after 300 min (M_n = 10 500, MMD = 1.23). The catalyst was reused a third time following separation of the product as above (Figures 1 and 2, Table 1). In both the second and third runs, the rate of polymerization is almost identical to that in the first run after the first 2 h. The M_n growth with conversion follows the same trend, and the final product is similar in all cases, with M_n from both products after the same degree of conversion being essentially identical when SEC and conversion errors are taken into account. If the apparent lowering of the M_n from runs 1−3 is real, this would be an indication that the initiator efficiency was increasing slowly between runs, which is considered unlikely at this time. It appears that during the first 2 h of run 1 an equilibrium is established between Cu(I) and Cu(II) species until steady-state conditions are established. Copper(II) acts as a deactivator in living radical polymerization and is formed as a result of radical−radical termination reactions.[29]

Table 1. Final Molecular Mass and Conversion Data for Polymers Synthesized in This Study at 90 °C for 300 Min, [MMA]/[**2**] = 100, [CuBr]/[**2**]/[**1**] = 1/1/1

polymer	M_n	PDi	conversion (%)[a]	k_p[pol*][b] × 10^3 s^{-1}
PMMA 1	11 100	1.30	76.6	3.68[c]
PMMA 2	10 500	1.23	57.7	2.99
PMMA 3	9 330	1.24	57.7	2.99
P(MMA-*b*-BzMA)[d]	28 900	1.48	97	

[a] Conversion from integration of ^{1}H NMR. [b] From slope of first-order kinetic plot in Figure 1. [c] Taken from final four points only. [d] 17.5 h with [BzMA]/[macroinitiator] = 100, [CuBr]/[**2**]/[macroinitiator] = 2/2/1.

To demonstrate that the reactions occurred under living polymerization conditions, a block copolymer was prepared by a reinitiation experiment. Poly(methyl methacrylate), isolated from runs 2 and 3, was combined and dissolved in toluene prior to being added to the perfluoromethylcyclohexane catalyst solution with degassed benzyl methacrylate, BzMA. Following heating at 90 °C for 17.5 h, a block copolymer of P(MMA-*b*-BzMA) was isolated with M_n = 28 900 ($M_{n\ theor}$ = 26 200) and MMD = 1.48. Size exclusion chromatography of the block copolymer with both UV and refractive index dual detectors gave almost identical responses with no sign of the polymer used as macroinitiator remaining (see Supporting Information). This indicates regrowth of the macroinitiator to give polymer that contains UV-active chromophores across the mass envelope, excellent evidence for the formation of a block copolymer. The block copolymer gave a single glass transition at 72.4 °C (predicted glass transition of 69 °C from the Flory equation). This is further excellent proof for a block copolymer, where the two blocks are miscible due to the low degree of polymerization of each block, enabling entropy of mixing to be overcome. A mixture of the two homopolymers, of similar mass, gave two glass transitions at 48 and 100 °C (see Supporting Information). ^{1}H and ^{13}C NMR data are also consistent with a block copolymer (see Supporting Information). Again, all products were isolated by the removal of volatiles from the hydrocarbon layer as colorless solids. It is noted that, when nondeoxygenated solvent is added to the catalyst solution, it immediately turns dark brown and is deactivated. Thus, it is very important to operate under strict oxygen-free conditions.

Hence, atom-transfer living polymerization proceeds very effectively under fluorous biphasic conditions. This allows for the facile separation of product from catalyst, leaving the catalyst in a reusable state, which gives very reproducible results after repeated uses.

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Supporting Information Available: Full molar mass and conversion data, selected SEC curves, full experimental details, and NMR and DSC spectra of block copolymer (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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