**Narrative Progress Report**
PRF# : 58014-DN17
Project Title: Development of Isotactic Controlled Radical Polymerization Using Rationally Designed Lewis Acids
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This proposal original aimed to develop a stereo-controlled living radical polymerization through which a broad range of monomers can be isotactically polymerized under highly accessible reaction conditions. This has been a long-standing challenge due to the inherent difficulty in controlling the stereochemistry of the planar configuration of the sp$^2$ hybridized carbon of the free radical. In the first reporting period, we have synthesized a series of nitroxide radicals tethered with a Lewis acid complex (Fig. 1a) for nitroxide-mediated polymerizations (NMPs). We hypothesized that the Lewis acid anchored on the nitroxide



**Fig. 1** The proposed mode for isotactic controlled radical polymerization assisted by Lewis acid.

radical can be coordinated by the heteroatoms in the active chain end, and therefore a consistent conformation can be retained at the active chain end (Fig. 1b). In this mode, the monomer will be more easily unidirectionally incorporated into the polymer chain end to construct the *m* diads through a pseudo-insertion type controlled/living radical polymerization.
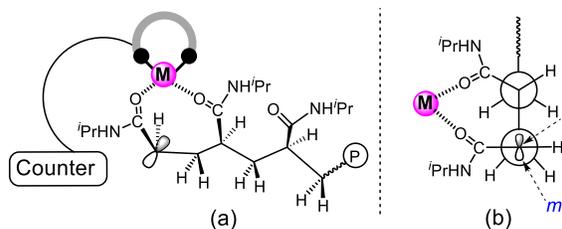
While The postdoctoral researchers – Drs. Feng Li and Fei Lin who were funded by the ACS PRF awarded – encountered difficulties in both synthesis of some proposed compound and observing solid evidence in the control over isotacticity, Dr. Li utilized an interesting compound – α-bromo butyl acrylate (BBA) that were obtained in one of the synthetic routes toward one of the compounds described in Fig. 1 – to realize an unusual chain-growth type controlled/living branching radical polymerization (CLBRP). Specifically, BBA can be used as a novel polymerizable initiator in atom transfer radical polymerization (ATRP) to synthesize well-defined hyperbranched polymers (HPs). This work has been published in *J. Am. Chem. Soc.* (DOI: 10.1021/jacs.8b12433). We hypothesized that copolymerization of BBA, an alkene halide, with conventional monomers under ATRP conditions leads to a CLBRP. This hypothesis is based on the following theoretical premises: (1) because the bond dissociation energy (BDE) of the C–Br bond in BBA is approximately 20 kcal/mol higher than the conventional ATRP initiators, e.g., ethyl α-bromoisobutyrate (EBiB) and ethyl 2-bromopropionate (EBP), BBA cannot be activated by regular ATRP activators to form a propagating radical; (2) BBA retains radical-copolymerizability with other monomers such as styrene, (meth)acrylates, and acrylonitrile; (3) the two C−Br bonds at the α-position of the alkyl dihalide intermediate (Scheme 1b), resulting from radical addition of BBA and subsequent deactivation, can both be re-activated, providing a branching junction. A new term inibramer is named to differentiate the unique role of BBA from conventional inimers – the initiation-based branching process in BBA occurs exclusively after it is incorporated into to a polymer chain as a monomer.

In early efforts to verify our hypothesis, one-pot copolymerization of *n*-butyl acrylate (*n*BA) and BBA was conducted under ATRP condi-tions using EBP as an initiator and *N,N,N',N'',N''*-pentamethyldiethylenetriamine (PMDETA) as the ligand for the Cu complexes. The distinct reactivity of BBA and *n*BA, reflected by the reactivity ratios of $r_{BBA} = 9.77$ and $r_{nBA} = 0.24$, led to consumption of BBA approximately 1 order of magnitude faster than *n*BA, indicating that a gradient compositional change from BBA-rich to *n*BA-rich segments was obtained in the copolymers. Since each radical addition to BBA introduces an additional initiating site, the excessive incorporation of BBA at the early stage resulted in an exponential increase in the concentration of propagating radicals, and polymer gelation was observed in all one-pot reactions due to the accelerated rate of radical termination. As a result, the overall polymerization rate decreased.

BBA was then slowly fed into the polymerization solution at various rates to regulate the cross-propagation reactions. This semi-batch strategy provided copolymerizations with suppressed termination and relatively uniform incorporation of the two comonomers (Table 1). For instance, gelation-free copolymerizations were achieved when 8 equivalents of BBA with respect to the EBP initiator was fed into ATRP of *n*BA at a feed rate of 0.2 eq./h (Entries 1 and 2). Copolymers with low dispersities ($Đ < 1.3$) were obtained, and kinetic data suggests that BBA was incorporated into the polymer products in a more uniform fashion compared to the one-pot copolymerizations. To evaluate the degree of branching (DB), a spacing value $S_n$ was defined as the average number of monomers inserted between two neighboring branching junctions, as the *n*BA comonomer does not contribute to the branching. Increasing the equivalence of *n*BA from 200 to 500 diluted the branching junctions and increased $S_n$ from 6.1 to 9.2.

## Table 1. CLBRP of BBA with $nBA^a$, $MA^b$, and St.$^c$

| Entry | $M_1/M_2/I^d$ | $M_1$ | Time (h) | Feed rate (eq./h) | Conv.(%) ($M_1/M_2$) | $M_{n,theo}$ (kDa) | $M_{n,GPC}$ (kDa) | $M_{n,MALLS}$ (kDa) | Đ | $S_n^j$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 500/8/1 | nBA | 50 | 0.2 | 17/50 | 11.6 | 10.1 | 12.4 | 1.28 | 9.2 |
| 2 | 200/8/1 | nBA | 52 | 0.2 | 22/37 | 6.3 | 5.5 | 6.9 | 1.21 | 6.1 |
| 3 | 500/12/1 | nBA | 48 | 0.4 | 17/53 | 12.1 | 9.2 | 11.5 | 1.35 | 6.1 |
| 4$^e$ | 500/12/1 | nBA | 46 | 0.4 | 15/42 | 11.1 | 8.8 | 11.5 | 1.37 | 7.0 |
| 5$^f$ | 500/20/1 | nBA | 66 | 0.4 | 18/49 | 13.7 | 8.1 | 12.9 | 1.57 | 4.4 |
| 6$^g$ | 500/20/1 | nBA | 71 | 0.4 | 17/44 | 12.8 | 7.8 | 11.8 | 1.45 | 4.5 |
| 7$^h$ | 500/20/1 | MA | 71 | 0.4 | 25/34 | 12.4 | 6.2 | 13.9 | 1.25 | 8.6 |
| 8 | 400/8/1 | St | 66 | 0.167 | 24/62 | 11.0 | 6.6 | 11.3 | 1.28 | 8.6 |
| 9 | 500/12/1 | nBA | 57 | 0.24 | 18/38 | 17.6 | 15.6 | ND | 1.20 | 8.9 |
| 10$^i$ | 400/12/1 | St | 53 | 0.25 | 27/68 | 18.1 | 14.5 | ND | 1.28 | 6.3 |

$^a$ Conditions for $nBA$: $[I]_0/[CuBr]_0/[CuBr_2]_0/[PMDETA]_0 = 1/0.9/0.2/1.2$, $n(I) = 0.10$ mmol or 0.075 mmol in anisole at 60 °C. $^b$ Conditions for MA: same as $nBA$ but at 65 °C. $^c$ Conditions for St: $[I]_0/[CuBr]_0/[CuBr_2]_0/[dNbpy]_0 = 1/0.95/0.05/2.0$, $n(I) = 0.10$ mmol or 0.075 mmol in anisole at 90 °C. (dNbpy = 4,4′-Dinonyl-2,2′-dipyridyl) $^d$ $M_2$ = BBA. I = EBP for Entries 1–7, EBiB for Entry 8, $PDMS_{66}$-BP ($M_n$ = 5.1 kDa) for Entry 9, and $PDMS_{66}$-BiB for Entry10. $^e$ Repeat for Entry 3. $^f$ Additional 0.5 eq. of CuBr/PMDETA in anisole was injected at 28 h in one dose. $^g$ Additional 0.5 eq. of CuBr/PMDETA in anisole was fed from 20 to 35 h. $^h$ Additional 0.5 eq. of CuBr/PMDETA was injected at 25 h in one dose. $^i$ Additional 0.15 eq. of Sn(EH)$_2$ in anisole was injected in separated two doses at 24 h and 45 h respectively. $^j$ $S_n$ = $DP_{M1}/(1+2\times DP_{BBA})$, DP = degree of polymerization.

The control over DB was further investigated by varying the feed ratio of BBA and $nBA$ (Entries 1, 3, 5, and 6). Increasing the feed amount of BBA from 8 to 12 equivalents yielded branched P$nBA$ with a smaller $S_n$. Further increase in the feed amount of BBA to 20 eq. led to a considerable decrease in polymerization rate at the late stage of slow feeding. Additional Cu$^I$Br/PMDETA activators were added via either one dose (Entry 5) or slow feeding (Entry 6) to sustain the polymerizations; highly branched P$nBA$ with $S_n$ as low as 4.4 was thus synthesized. To confirm the branched structures, $^{13}$C NMR spectra of P$nBA$ with different DBs, but similar absolute molecular weights ($M_{n,MALLS}$) determined by multi-angle static light scattering, were compared (Figure 1a). When more BBA were integrated in the polymers, the peak intensity for polymer chain end moiety and quaternary carbon center increases. The $^{13}$C NMR spectra also indicate that all polymerized BBA participated in the branching process due to the absence of tertiary C–Br structure (chemical shift 66–67 ppm). This nearly quantitative branching efficiency is corroborated by density functional theory calculation – the ATRP activities of alkyl dibromide and tertiary alkyl bromide, both originating from BBA, are respectively 2 and 1 order of magnitude higher than the secondary alkyl bromide chain end in P$nBA$.

To further evaluate the quality of control in these copolymerizations, $M_{n,MALLS}$ was compared with the theoretical number-average molecular weight ($M_{n,theo}$) calculated based on the monomer conversion. In branched P$nBA$ samples with small $S_n$ (e.g., Entries 5–6), the large discrepancy between $M_{n,theo}$ and $M_{n,GPC}$, i.e., the molecular weight estimated by gel permeation chromatography (GPC), can be ascribed to their more compact conformations and corresponding smaller hydrodynamic volumes compared to P$nBA$ with similar $M_{n,theo}$ but larger $S_n$ (e.g., Entry 1). In contrast, $M_{n,MALLS}$ exhibits excellent agreement with $M_{n,theo}$ (Table 1). $M_{n,MALLS}$ tested at different monomer conversions (for Entry 4) increased linearly with the $M_{n,theo}$ when the $nBA$ conversion exceeded about 10% (Figure 1b, red dots). This linear correlation demonstrates that a controlled polymerization was achieved and the deviation at low conversion could be attributed to low initiation efficiency.
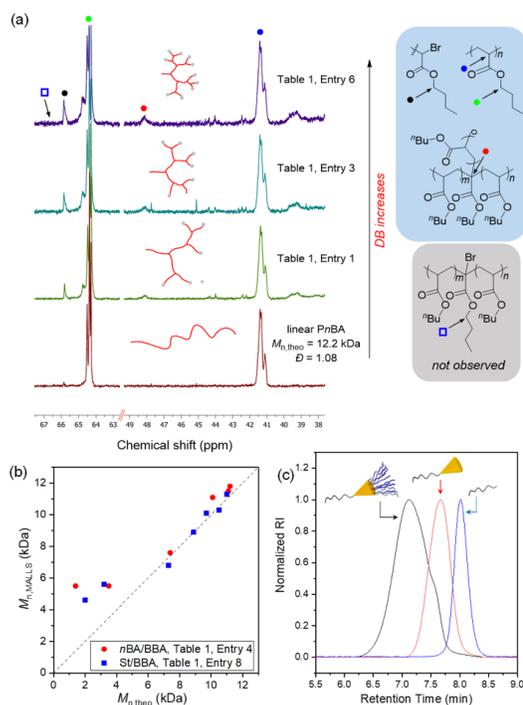


**Fig. 2.** (a) $^{13}$C NMR spectra of P$nBA$ with different DBs; (b)$M_{n,MALLS}$ vs. $M_{n,theo}$ plots for CLBRPs of BBA with $nBA$ and St; (c) GPC traces of $PDMS_{66}$-BP macroinitiator (blue), $PDMS_{66}$-$b$-P($nBA_{90}$-$co$-BBA$_5$) (red), and $PDMS_{66}$-$b$-P($nBA_{90}$-$co$-BBA$_5$)-$b$-PSt$_{319}$ (black).