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Tailoring the $\text{AlCl}_3/\text{iPr}_2\text{O}/\text{Et}_2\text{O}$ initiation system for highly reactive polyisobutylene synthesis in pure *n*-hexane

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This paper reports the flow synthesis of highly reactive polyisobutylenes (HRPIBs) in pure *n*-hexane using properly prepared $\text{AlCl}_3 \cdot \text{Et}_2\text{O}$ crystals in conjunction with $\text{AlCl}_3 \cdot \text{iPr}_2\text{O}$ solution as coiniciators. By preparing $\text{AlCl}_3 \cdot \text{iPr}_2\text{O}$ solution and $\text{AlCl}_3 \cdot \text{Et}_2\text{O}$ crystals separately, the cationic polymerization of isobutylene proceeded smoothly under a wide range of monomer concentrations (0.33–1.30 M) in the presence of H_2O as an initiator, affording a high yield (~89%) and a moderate exo-olefin terminal group content (60–75%) in 10 min. The various functions of iPr_2O and Et_2O in the initiator solution were comprehensively revealed from the polymerization results, attenuated total reflection-Fourier transform infrared and ^{27}Al nuclear magnetic resonance spectra, and density functional theory simulations. $\text{AlCl}_3 \cdot \text{iPr}_2\text{O}$ was confirmed to be the key component that stabilized carbenium ions. The $\text{AlCl}_3 \cdot \text{Et}_2\text{O}$ complex was the key component to promote proton elimination. Free Et_2O should be removed to inhibit its negative effect on isomerization. This new strategy may lead to high commercial interest in HRPIB synthesis in pure green solvent and could potentially be extended to other initiation systems containing solid Lewis acids.

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Introduction

Polyisobutylenes (PIBs), the most important industrial products of cationic polymerization, are characterized by their thermal stability, flexibility at ambient temperature, and impermeability to gases.^{1–5} Therefore, PIBs have been widely used in automobile tires, medical bottle plugs, additives of fuels, and lubricants.^{6–9} Highly reactive polyisobutylenes (HRPIBs),^{10,11} which are PIBs with high contents of exo-olefin end groups (≥ 60 mol%) and a specific molecular weight distribution ($M_n = 500$ –5000), are highly reactive intermediates in the preparation of additives for lubricants and fuels. Thus, HRPIBs attract considerable attention from both industry and academia. The commercial synthesis of HRPIBs is dominated by the cationic polymerization of isobutylene (IB) using BF_3 as a coiniciator and traces of alcohol or water as an initiator at temperatures slightly below 0 °C in *n*-hexane.^{10,12} However, BF_3 is costly and strongly corrosive, resulting in serious economic and safety concerns.¹³

In a series of publications, novel and economic catalyst systems were reported to produce HRPIBs with high exo-olefin content,¹⁴ such as $\text{FeCl}_3/\text{iPrOH}$,^{8,15} $\text{FeCl}_3/\text{iPr}_2\text{O}$,^{7,16–18} and $\text{AlCl}_3/\text{ether}$. Among the various coiniciators, solid AlCl_3 has the advantages of low cost and high activity; however, it is always accompanied by the use of chlorinated solvents like

CH_2Cl_2 ,^{9,19–26} at least in the preparation of initiator solution. Considering the environmental and health impacts of chlorinated solvents, it is highly desirable to completely replace them with green solvents such as *n*-hexane. However, the low stability of the carbenium ions in nonpolar solvents generally results in low conversion and poor controllability,²⁷ making it difficult to effectively obtain HRPIBs in pure *n*-hexane.

The proper stabilization of carbenium ions and effective β -proton elimination, which are known as the keys to preparing HRPIBs,^{21,23,25,28,29} depend on the careful regulation of active centers and chain reactions. Our previous investigations have shown that introducing nucleophilic reagents into the initiator solution is an effective and direct method to adjust the active centers and chain reactions when using AlCl_3 as a coiniciator.^{29–31} In detail, strongly basic Et_2O can decrease the acidity of AlCl_3 *via* complexation and inhibit its catalysis of H_2O dissociation, which can stabilize carbenium ions and decrease the polymerization rate in $\text{CH}_2\text{Cl}_2/n$ -hexane solvent mixtures. Meanwhile, the free Et_2O significantly promotes proton elimination and isomerization, resulting in a high conversion rate and a low content of exo-olefin. Similarly, iPr_2O can stabilize carbenium ions and promote proton elimination in CH_2Cl_2 . However, iPr_2O has little influence on isomerization due to steric hindrance, leading to a high content of exo-olefin.³² From these results, it can be concluded that Et_2O may have a stronger influence on the rate of β -H abstraction in pure *n*-hexane, while iPr_2O may better stabilize the carbocations.

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Herein, we present a novel and simple method to prepare effective initiation solutions in *n*-hexane with a special focus on the synergistic effects of nucleophilic reagents ($i\text{Pr}_2\text{O}$ and Et_2O) on AlCl_3 -catalyzed IB polymerization. HRPIBs with high conversion rates and exo-olefin contents were successfully synthesized by comprehensively regulating carbenium ion stability, reactivity, and proton elimination. Moreover, attenuated total reflection-Fourier transform infrared (ATR-FTIR) spectroscopy, and ^{27}Al nuclear magnetic resonance (NMR) spectroscopy were combined with density functional theory (DFT) simulation to reveal how the controlled polymerization process was achieved in pure *n*-hexane.

Experimental methods

Materials

n-Hexane (C_6H_{14} , 97.5+%, anhydrous), isopropyl ether ($i\text{Pr}_2\text{O}$, 99.0+%), and aluminum chloride (AlCl_3 , 99+%, anhydrous) were purchased from J&K Scientific (China). Diethyl ether (Et_2O , 99.5+%) and ethanol (analytical reagent) were obtained from Sinopharm Chemical Reagent Co. Ltd (China). IB (99.9+%, anhydrous) was obtained from Dalian Special Gases Co., LTD (China) and used directly as received. *n*-Hexane was dried over Solvent Purification Assembly (VAC, USA), and the content of water was determined using a coulometric Karl Fischer moisture meter (Mettler Toledo, Switzerland). $i\text{Pr}_2\text{O}$ and Et_2O were distilled to remove stabilizer and then dried over Molecular Sieves 5A overnight. $i\text{Pr}_2\text{O}$, Et_2O , AlCl_3 , and *n*-hexane were preserved in a glovebox (Mikrouna, China). The content of AlCl_3 in the initiator solution was measured by ultraviolet-visible spectrophotometry (UV-2450, Shimadzu).

Polymerization of IB

The polymerization of IB was performed in a microflow system composed of three T-shaped micromixers (M1 for the mixing of IB and diluent in *n*-hexane; M2 for the mixing of IB solution and initiator solution; and M3 for the injection of terminator agent in ethanol), two precooling (or preheating) coiled stainless tubes (C1 and C2, inner diameter = 900 μm), and a microtube reactor (R, inner diameter = 900 μm), as shown in Fig. 1. The polymerization of IB proceeded in R1, and the reaction time could be adjusted by the flow rate and the length of R1. Four syringe pumps were used to deliver IB, *n*-hexane, initiator solution, and terminator at flow rates of 2, 6, 8, and 2 mL min^{-1} , respectively. IB was transferred as a liquid from the bottom of the IB cylinder into the syringe and then mixed with *n*-hexane in the tube as a liquid under a pressure of 3 bar.^{29,31}

Preparation of initiation solution

The initiation solution was prepared just before polymerization in a glove box under an argon atmosphere. Seven preparation methods with single or double ethers were studied in this work. (a) Method 1: dry *n*-hexane was added to AlCl_3 powder, and then slight excess Et_2O was added to form the initial solution. (b) Method 2: dry *n*-hexane was added to AlCl_3 powder, and then slight excess $i\text{Pr}_2\text{O}$ was added. Since AlCl_3 powder could not be

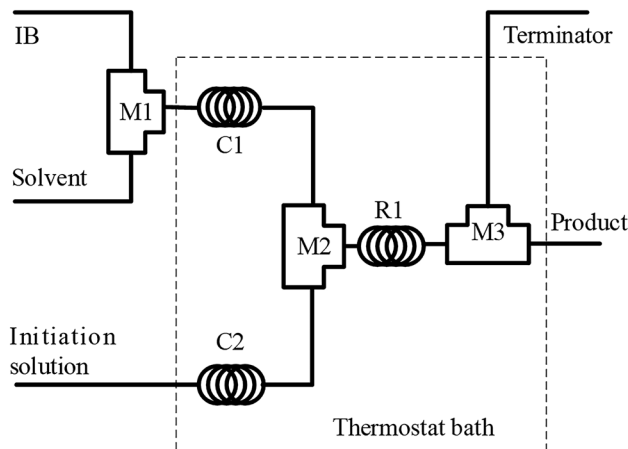


Fig. 1 Schematic diagram of the flow synthesis setup. M1, M2, and M3 are T-shaped micromixers; C1 and C2 are curved tubes for achieving the pre-set temperature; and R1 is a microtube reactor.

completely dissolved in this case, the upper layer was withdrawn as an initiation solution, denoted as solution A. (c) Method 3: dry *n*-hexane was added to AlCl_3 powder, and an appropriate amount of Et_2O was then added. After several minutes, dry $i\text{Pr}_2\text{O}$ was added. The solution was used as an initiation solution. (d) Method 4: dry *n*-hexane was added to AlCl_3 powder, and then an appropriate amount of $i\text{Pr}_2\text{O}$ was added. After stirring for 2 h, dry Et_2O was added. The solution was used as an initiation solution. (e) Method 5: dry Et_2O was added into solution A to form the initial solution. (f) Methods 6 and 7. Dry Et_2O (method 6), *n*-hexane/ Et_2O mixture [5/2 (v/v), method 7], or separate *n*-hexane and Et_2O (method 7-1) was added to AlCl_3 powder and then vacuumed to form a colorless crystal B. Solution A was added to crystal B under stirring to form the initiation solution (Fig. 2).

Characterization

Size-exclusion chromatography. The molecular weight and dispersity value (\mathcal{D}) of the polymers were measured using a Waters gel permeation chromatography (GPC) system comprised of a Waters 2707 autosampler, a 1515 Isocratic high-performance liquid chromatography pump, a 2414 refractive index detector, and three Styragel GPC columns [Styragel HT3, HT4, HT5; column size = 7.8×300 mm; particle size = 10 μm]. The molecular weight could be detected in the range of $500\text{--}4 \times 10^6$. The system was thermostated at 38 $^\circ\text{C}$. Tetrahydrofuran was used as the eluent at a flow rate of 1.0 mL min^{-1} . The instrument was calibrated with polystyrene standards. The results were processed by Breeze 2 software (Waters).

ATR-FTIR spectroscopy. The ATR-FTIR spectra were recorded *in situ* using a Mettler Toledo ReactIR 15 instrument with a DiComp probe coupled to a mercury cadmium telluride detector *via* AgX fiber. Each spectrum was collected every 256 s by accumulating 256 scans with a wavenumber resolution of 4 cm^{-1} over the spectral range of 650–3000 cm^{-1} . The ATR-FTIR



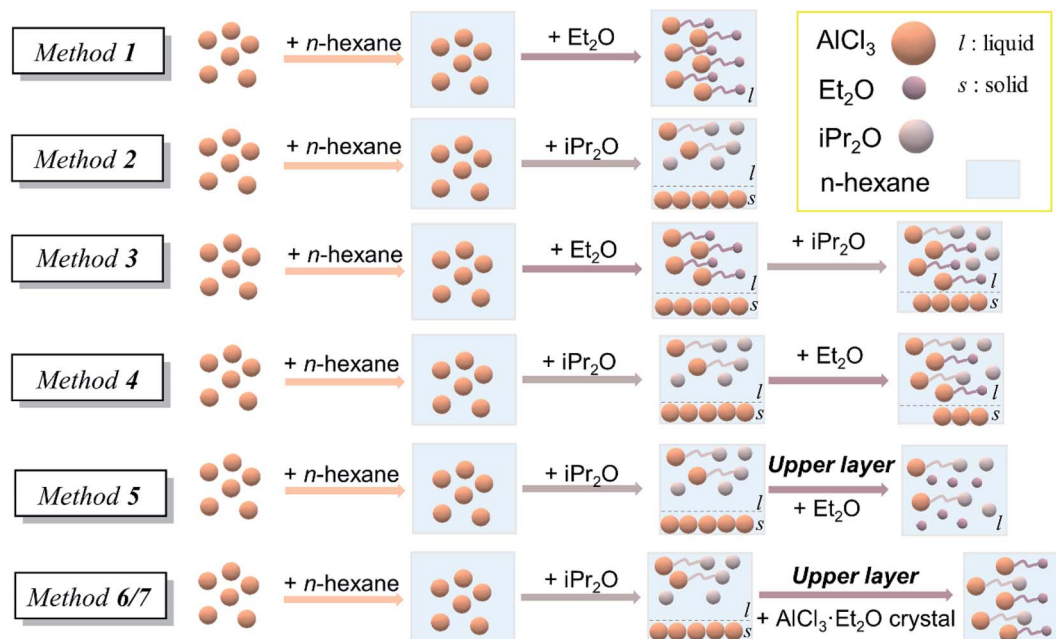


Fig. 2 Schematic of various preparation methods of initiation solution.

spectrum of diluent (*n*-hexane or CH_2Cl_2) was chosen as the background. The measurement temperature was 25 °C.

NMR spectroscopy. The ^{27}Al NMR spectra were measured using a JNM-ECA 600 MHz spectrometer using $[\text{Al}(\text{OD})_6]^{3-}$ in a capped capillary as both an internal standard and lock ($[\text{Al}(\text{D}_2\text{O})_6]^{3+}$, 0 ppm).^{33–37}

^1H NMR spectra were recorded on a JNM-ECA 600 MHz spectrometer with CDCl_3 as the solvent. The PIB end-group content was calculated from the ^1H NMR spectra. Fig. 3 shows a typical ^1H NMR spectrum; the main resonance signals are located at $\delta = 1.1$ ppm (z), 1.41 ppm (y), 0.99 ppm (x), 4.85 ppm

(a1), 4.64 ppm (a2), 5.17 ppm (c1), 5.37 ppm (c2), 5.15 ppm (d), and 2.83 ppm (e). The two characteristic protons of the exo-olefin end group (structure A, protons a1 and a2) appear as two well-resolved peaks at 4.85 and 4.64 ppm, respectively. Small amounts of the *E* and *Z* configurations of the tri-substituted olefin end group (structure C, protons c1 and c2) appear at 5.37 and 5.17 ppm, respectively. The one characteristic proton of the endo-olefin end group (structure D, proton d) appears at 5.15 ppm. The signal corresponding to the tetra-substituted olefin end group (structure E, proton e) appears as a broad multiplet at 2.85 ppm. The methylene, methyl, and end methyl protons of the PIB chains (structure A, protons y, z, and x, respectively) typically appear at 1.41, 1.11, and 0.99 ppm, respectively.

DFT calculations. The binding energies of different AlCl_3 /ether complexes were determined by *ab initio* calculations using Gaussian 09W at the B3LYP level of theory. The Pople basis set 6-311G(++, d, p) was used for all atoms in the solvent, and SMD was used as the solvation model.

Results and discussion

Synergistic effects of Et_2O and iPr_2O on AlCl_3 -initiated IB polymerization in pure *n*-hexane

We first determined the polymerization characteristics using only Et_2O or iPr_2O . The polymerization results are shown in Table 1; method 1 and method 2 correspond to the introduction of only Et_2O and only iPr_2O , respectively. The ether/ AlCl_3 molar ratio was controlled over unity as a prerequisite to ensuring a high content of exo-olefin according to previous reports on HRPIB synthesis.^{8,29,38} As shown in Table 1, the exo-olefinic end-group content ($\sim 24\%$) and yield ($\sim 18\%$) obtained using method 1 are relatively high. In contrast, with method 2, the IB

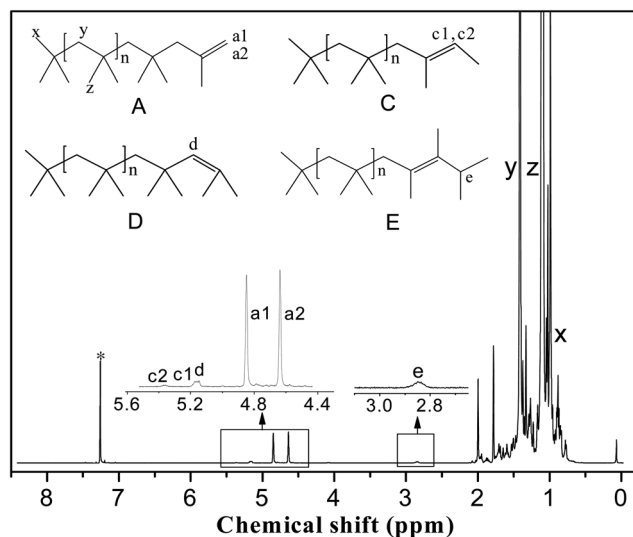


Fig. 3 Typical ^1H NMR spectrum of PIB. The asterisk denotes the CHCl_3 resonance.



Table 1 Polymerization of IB catalyzed by AlCl₃ with Et₂O or iPr₂O in pure *n*-hexane^a

Entry	Method	<i>t</i> (s)	[AlCl ₃] _I (mM)	Conv. (%)	<i>M</i> _n	<i>D</i>	[PIB]/mM	Exo (%)	Tri + endo (%)	Tetra (%)
1	1	60	10.51	12	5189	2.76	0.82	ND ^b	ND	ND
2		600	10.51	18	4664	4.15	1.41	24	48	28
3	2	60	2.20	3	3828	2.05	0.25	ND	ND	ND
4		600	2.20	5	4074	2.75	0.46	15	85	0

^a *F*_{total} = 16 mL min⁻¹; [IB] = 1.3 M; *T* = 0 °C; [H₂O] = 0 (control) mM, for method 1: [Et₂O] = 15 mM, for method 2: [iPr₂O] = 15 mM. Conv.: gravimetric conversion. ^b Not determined.

conversion and exo-olefinic end-group content were only 3–5% and 15%, respectively. However, in contrast to the initiation solution prepared in CH₂Cl₂ ($\epsilon = 9.08$),²⁹ the initiation solution prepared in pure *n*-hexane ($\epsilon = 1.89$) afforded PIBs mainly containing endo-, tri-, and tetra-substituted double bonds and having polydispersity indices (PDIs) around 2.0 or higher. Meanwhile, the IB conversions were low (<20%) and seemed to be independent of residence time in the range of 60–600 s. We supposed that the AlCl₃·Et₂O or AlCl₃·iPr₂O complex could only generate ionic species with low reactivity or poor stability in pure *n*-hexane, which may be attributed to the weak ionization in the nonpolar solvent.^{39–41}

Considering that Et₂O or iPr₂O alone did not work for HRPIB preparation in pure *n*-hexane, we attempted to use double ethers to simultaneously regulate the reactivity and stability of ionic species in initiation solution. iPr₂O was expected to stabilize carbenium ions, while Et₂O was expected to promote proton elimination as the key for end group control.

The results of polymerizations utilizing various preparation strategies for initiation solution are summarized in Table 2. For method 3, the IB conversion was similar to that of method 1 (only Et₂O), while the exo-olefin content was reduced to 13%. The subsequent addition of iPr₂O had little influence on the stability and reactivity of growing species mainly cointiated by AlCl₃·Et₂O and weakened the β -H elimination effect of Et₂O to some extent. In contrast, when reversing the addition sequence of the two ethers (method 4), the obtained PIBs had a much higher exo-olefin content (up to 35%). This may be attributed to the effect of Et₂O on the proton elimination of growing species mainly cointiated by AlCl₃·iPr₂O. In addition, since approximately half of the added AlCl₃ remained undissolved in method 4, all existing forms of Et₂O in the upper layer were AlCl₃·Et₂O

complexes, which might also play a role in inducing chain initiation and β -H elimination. To confirm this assumption, we used the initiation solution prepared by method 5, in which undissolved AlCl₃ at the bottom was removed followed by the addition of Et₂O. As seen in entry 10, the content of exo-olefin end groups decreased slightly to 29%, and the conversion decreased seriously. This indicates that free Et₂O inhibits the reactivity of the growing species cointiated by AlCl₃·iPr₂O, and AlCl₃·Et₂O may be critical to facilitate conversion and end group control. Thus, for the growing species cointiated by AlCl₃·iPr₂O, we speculated that weak ionization in conjunction with slow chain transfer could be overcome by introducing AlCl₃·Et₂O only. To this end, we removed the free Et₂O during AlCl₃·Et₂O preparation *via* vacuum to obtain AlCl₃·Et₂O crystals. Meanwhile, *n*-hexane was added to the AlCl₃ powders before adding Et₂O to regulate the interaction between AlCl₃ and Et₂O and facilitate the removal of free Et₂O (methods 6 and 7).

As seen in Table 3, the cationic polymerization of IB with methods 6 and 7 in pure *n*-hexane proceeded smoothly; relatively high monomer conversions (21–89%) were achieved within 10 min, affording HRPIBs with comparable contents of exo-olefin terminal groups in the range of 60–75%. The number-average molecular weight (*M*_n) increased slightly with polymerization time, and the polydispersity index was less than 2.0 in most cases. These results indicate that isomerization *via* carbenium ion rearrangement could be suppressed to some extent. From entries 15 and 16, it is apparent that adding *n*-hexane/Et₂O mixture is important to achieve higher conversion. The addition of *n*-hexane in method 7 may weaken the interaction between AlCl₃ and Et₂O, resulting in higher conversion (~89%). This confirmed that the appropriate activity and

Table 2 Polymerization of IB catalyzed by AlCl₃ with dual ethers (Et₂O and iPr₂O) in pure *n*-hexane^a

Entry	Method	<i>t</i> (s)	[AlCl ₃] _I (mM)	Conv. (%)	<i>M</i> _n	<i>D</i>	[PIB] (mM)	Exo (%)	Tri + endo (%)	Tetra (%)
5	3	60	11.09	3	ND	ND	ND ^b	ND	ND	ND
6		600	11.09	17	4183	2.94	1.44	13	87	0
7	4	60	8.92	7	3382	3.27	0.77	32	52	16
8		600	8.92	15	3576	2.20	1.54	35	57	8
9	5	60	3.30	3	4126	2.01	0.25	ND	ND	ND
10		600	3.30	4	ND	ND	ND	29	71	0

^a *F*_{total} = 16 mL min⁻¹; [IB] = 1.3 M; *T* = 0 °C; [H₂O] = 0 (control) mM. [Et₂O]₀ = 7.86 mM, [iPr₂O]₀ = 7.14 mM. Conv.: gravimetric conversion. ^b Not determined.



Table 3 Polymerization of IB catalyzed by AlCl₃ with dual ethers (Et₂O and iPr₂O) and a precise ratio of ether/AlCl₃ in pure *n*-hexane^a

Entry	Method	<i>t</i> (s)	[AlCl ₃] _I (mM)	Conv. (%)	<i>M</i> _n	<i>D</i>	[PIB] (mM)	Exo (%)	Tri + endo (%)	Tetra (%)
11	6	60	12.98	5	1271	1.61	1.39	ND ^b	ND	ND
12		600	12.98	21	1464	2.01	5.15	75	19	6
13	7	60	13.21	36	1629	1.91	8.03	60	30	10
14		600	13.21	89	1647	2.23	19.66	52	29	20
15	7-1	60	13.31	6	4117	1.23	0.554	ND	ND	ND
16		600	13.31	33	4302	1.23	2.755	68	20	12

^a *F*_{total} = 16 mL min⁻¹; [IB] = 1.3 M; *T* = 0 °C; [H₂O] = 0 (control) mM. [Et₂O]₀ = 7.86 mM, [iPr₂O]₀ = 7.14 mM. [AlCl₃]_A = 1.62 mM, Conv.: gravimetric conversion. ^b Not determined.

stability of active species could be obtained by combining double ethers and precise control of the ether/AlCl₃ ratio. As a result, HRPIBs could be obtained in under a wide range of IB concentrations (Table 4). To the best of our knowledge, this is the first example of the effective preparation of HRPIBs with AlCl₃ as a coinitiator in pure *n*-hexane.

Proposed mechanism of IB polymerization under dual ethers in pure *n*-hexane

In this section, ATR-FTIR and ²⁷Al NMR spectroscopies were used to gain further insight into the role of the dual ethers (Et₂O and iPr₂O). The ATR-FTIR spectra are presented in Fig. 4. The characteristic peak of the C–O bond in free Et₂O is located at 1126 cm⁻¹, while the characteristic peaks of free iPr₂O are situated at 1113, 1126, and 1171 cm⁻¹. For AlCl₃·Et₂O solution using method 1, the peak at 1126 cm⁻¹ was not detected, and two new and broad peaks appeared at 884 and 1005 cm⁻¹. For AlCl₃·iPr₂O solution using method 2, free iPr₂O molecules still existed. This may be because iPr₂O is present in excess with respect to AlCl₃ due to the poor solubility of AlCl₃ in iPr₂O with relatively large steric hindrance.

As shown in Fig. 5, when using dual ethers, the characteristic peaks for ether C–O bond stretching were redshifted, and a peak emerged at 999 cm⁻¹ (methods 3, 4, 6, and 7), suggesting that the interaction between AlCl₃ and C–O was enhanced. More interestingly, the intensities of the peaks around 999 cm⁻¹, which correspond to the Al–O bond, were significantly enhanced in the initiation solutions prepared with methods 6 and 7. This enhancement was positively correlated with the IB conversion. These results suggest that the coinitiators formed

in methods 6 and 7 were beneficial for ionizing H₂O and stabilizing the carbocations. However, compared to the different polymerization results obtained using methods 3, 4, 6, and 7, their ATR-FTIR spectra were difficult to distinguish; thus, it is necessary to consider other methods to characterize the interaction between AlCl₃ and ether.

To clarify the nature of different AlCl₃·ether complexes, *ab initio* calculations were conducted to determine the AlCl₃·ether binding energies. As shown in Fig. 6, the binding energies between AlCl₃ and iPr₂O were 33.07 kcal mol⁻¹ in CH₂Cl₂ and 30.49 kcal mol⁻¹ in *n*-hexane; the binding energies between AlCl₃ and Et₂O were 30.95 kcal mol⁻¹ in CH₂Cl₂ and 28.14 kcal mol⁻¹ in *n*-hexane. On the other hand, for the same complexes, the binding energies in nonpolar solvent (*n*-hexane) were relatively low. These results indicate that the stability of AlCl₃·Et₂O was less than that of AlCl₃·iPr₂O, and the stability further decreased with decreasing solvent polarity.

Herein, we further studied the interaction between AlCl₃ and ether in *n*-hexane by ²⁷Al NMR spectroscopy (Fig. 7). A single resonance was detected in all cases, indicating that the complexes of AlCl₃ and ether or the microenvironment around AlCl₃ were uniform. In addition, according to the position of this characteristic peak, the stabilities of the different AlCl₃·ether complexes decreased in the order of method 2, method 4, method 3, method 6, method 7, method 5, and method 1, consistent with the DFT simulations. Methods 6 and 7, which permitted faster polymerization and effective β-H abstraction, resulted in intermediate complex stability.

In detail, the ²⁷Al NMR signal of AlCl₃·iPr₂O (method 2) shifted even further toward lower frequency (higher field) compared to that of AlCl₃·Et₂O (method 1). This means that

Table 4 Polymerization of IB catalyzed by AlCl₃ with different IB concentrations in *n*-hexane^a

Entry	[IB] (M)	<i>t</i> (s)	[AlCl ₃] _I (mM)	[AlCl ₃] _A (mM)	Conv. (%)	<i>M</i> _n	<i>D</i>	Exo (%)	Tri (%)	Tetra (%)
17	0.33	60	10.98	3.80	29	1880	2.01	73	13	14
18	0.33	600	10.98	3.80	65	1460	2.08	72	15	13
19	0.65	60	11.28	3.75	23	4440	1.91	63	22	15
20	0.65	600	11.28	3.75	56	3730	2.06	58	26	16
21	1.30	60	11.06	3.79	15	6020	2.20	63	20	17
22	1.30	600	11.06	3.79	30	6500	2.25	61	21	18

^a *F*_{total} = 16 mL min⁻¹; *T* = 0 °C; [H₂O]₀ = 0.45 mM; [iPr₂O]₀ = 7.14 mM. Conv.: gravimetric conversion.



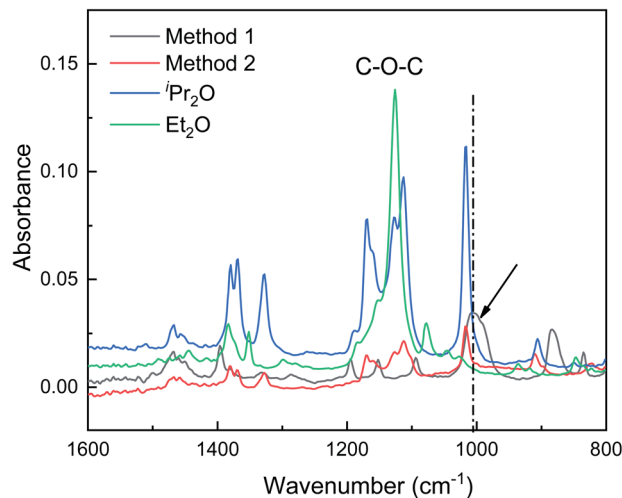


Fig. 4 ATR-FTIR spectra showing the interactions between AlCl_3 and ether in initiation solutions prepared with methods 1 and 2. The arrow and dash line indicate the peak corresponding to Al–O bond.

$i\text{Pr}_2\text{O}$ has a stronger electron-donating ability and a greater effect on the microenvironment around the Al atom. In other words, the interaction between AlCl_3 and $i\text{Pr}_2\text{O}$ is relatively strong in n -hexane, resulting in low reactivity for the ionization of H_2O and inducing transfer side reactions (isomerizations). The interaction between AlCl_3 and Et_2O is comparatively weak; thus, the $\text{AlCl}_3 \cdot \text{Et}_2\text{O}$ in $\text{H}_2\text{O}/\text{AlCl}_3 \cdot \text{Et}_2\text{O}$ initiation system (method 1) has high reactivity for H_2O ionization. However, free Et_2O may promote isomerization and increase the amount of endo-double bond terminal groups in the products. For method 3, weaker $\text{AlCl}_3 \cdot \text{Et}_2\text{O}$ was formed at the first stage, and the subsequently added $i\text{Pr}_2\text{O}$ may distribute around $\text{AlCl}_3 \cdot \text{Et}_2\text{O}$; however, its effect on Al atom may be weak due to steric hindrance. Thus, the microenvironment of the Al atoms was dominated by Et_2O . In contrast, in method 4, stronger

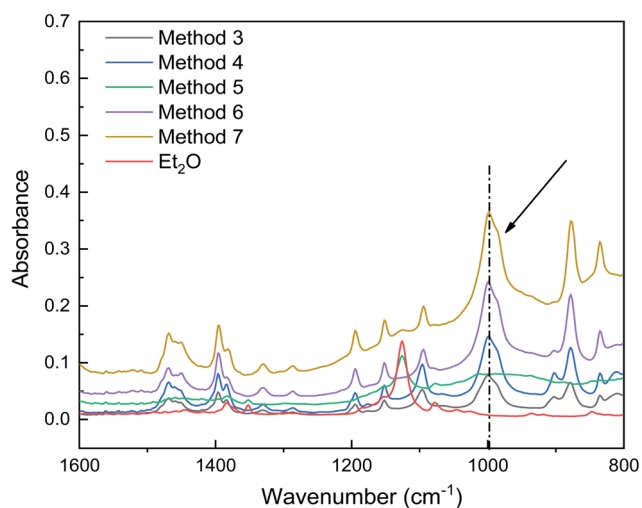


Fig. 5 ATR-FTIR spectra showing the interaction between AlCl_3 and ether in initiation solutions prepared using methods 3–7.

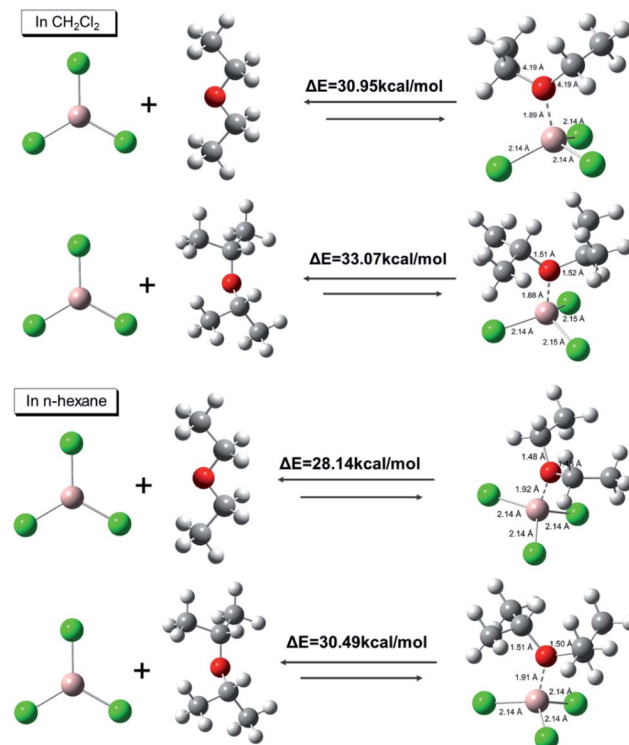


Fig. 6 DFT binding energies and optimized structures of $\text{AlCl}_3 \cdot \text{ether}$ calculated using Gaussian 09W [B3LYP/6-311G(++, d, p), solvation model: SMD]. Distances are in Å.

$\text{AlCl}_3 \cdot i\text{Pr}_2\text{O}$ was formed first, and some added Et_2O bound with AlCl_3 powder; thus, the microenvironment of Al atom in solution reflected the effect of $i\text{Pr}_2\text{O}$ to some extent. For method 5, all the added free Et_2O was distributed around $\text{AlCl}_3 \cdot i\text{Pr}_2\text{O}$, and the interaction between them caused the ^{27}Al shift to be closer to that of $\text{AlCl}_3 \cdot \text{Et}_2\text{O}$. Under the precise control of the $\text{AlCl}_3 \cdot \text{Et}_2\text{O} : \text{Et}_2\text{O}$ ratio (methods 6 and 7), higher activity for $\text{AlCl}_3 \cdot i\text{Pr}_2\text{O}$ was endowed by introducing suitable $\text{AlCl}_3 \cdot \text{Et}_2\text{O}$ complex to regulate the micro surroundings of $\text{AlCl}_3 \cdot i\text{Pr}_2\text{O}$ properly. In general, the interaction between AlCl_3 and Et_2O inhibited the isomerization effect of free Et_2O and regulated the effect of Et_2O on $\text{AlCl}_3 \cdot i\text{Pr}_2\text{O}$ toward compromised stability and reactivity.

Based on the above observations, we proposed that $\text{AlCl}_3 \cdot \text{Et}_2\text{O}$ might play two roles: participate in the initiation step, which is attributed to the weak interactions between AlCl_3 and Et_2O ; and accelerate effective β -H elimination since Et_2O was modified by AlCl_3 . The complexation between AlCl_3 and Et_2O may also inhibit the effect of Et_2O on internal proton transfer and abstraction. Meanwhile, $\text{AlCl}_3 \cdot i\text{Pr}_2\text{O}$ at a relatively low concentration rarely produced active centers. However, it could modify the stability of cation centers *via* solvation.

Scheme 1 shows the proposed mechanism of the cationic polymerization of IB using the $\text{AlCl}_3/\text{Et}_2\text{O}/i\text{Pr}_2\text{O}$ system in pure n -hexane. In detail, modified Et_2O with the assistance of $i\text{Pr}_2\text{O}$ provided the proper microenvironment around AlCl_3 . AlCl_3 then catalyzed the ionization of H_2O and generated considerable stable ionic species. Subsequently, the chain reactions were controlled by the selective β -H abstraction of modified



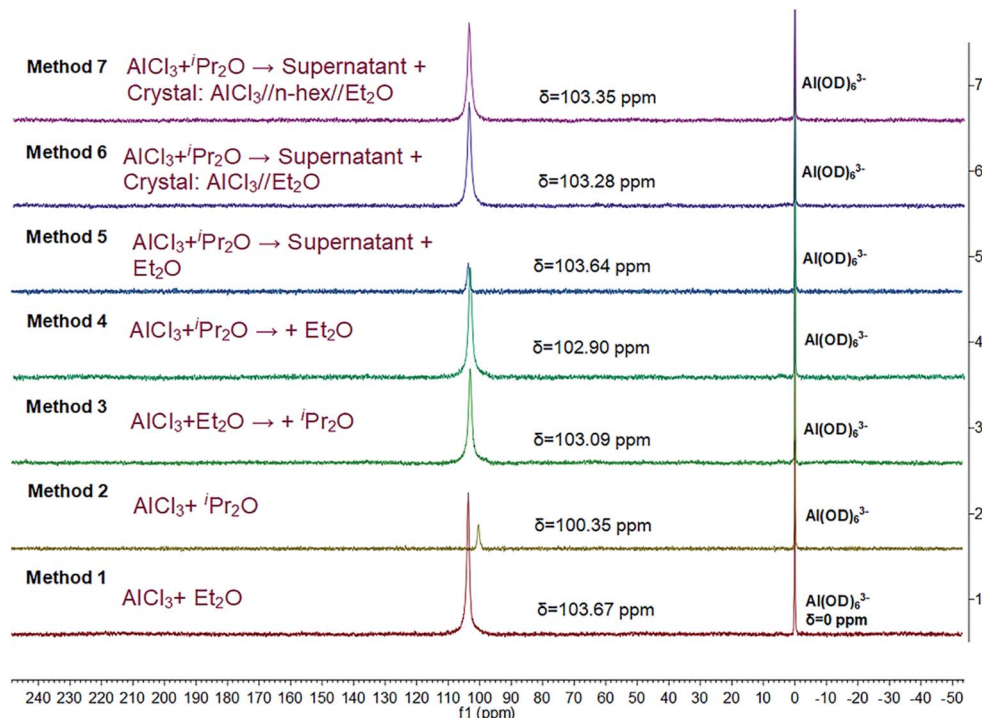
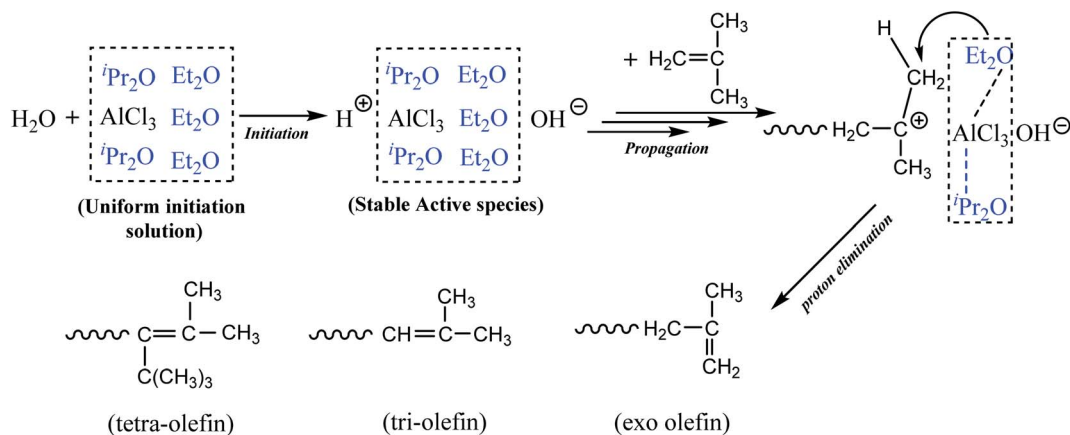


Fig. 7 ^{27}Al NMR spectra of initiation solutions prepared using different methods.



Scheme 1 Proposed mechanism of the cationic polymerization of IB using dual ethers.

Et_2O , resulting in higher conversion and a greater content of exo-olefin. In addition, the use of *n*-hexane weakened the interaction between AlCl_3 and Et_2O , facilitating the removal of free Et_2O and inhibiting undesired proton transfer.

Conclusion

In summary, an efficient strategy combining the precise control of the ether/ AlCl_3 ratio and the use of two nucleophilic reagents ($i\text{Pr}_2\text{O}$ and Et_2O) was developed to synthesize HRPIBs in pure *n*-hexane, resulting in 89% conversion with 60–75% exo-double bond content within 10 min. Among the AlCl_3 -ether complexes prepared with different preparation methods, good

performance in terms of both IB conversion and exo-olefin content was achieved by preparing $\text{AlCl}_3 \cdot i\text{Pr}_2\text{O}$ solution and $\text{AlCl}_3 \cdot \text{Et}_2\text{O}$ crystals separately. The various functions of $i\text{Pr}_2\text{O}$ and Et_2O in the initiator solution were comprehensively revealed based on the polymerization results, ATR-FTIR and ^{27}Al NMR spectra, and DFT simulations. The results confirmed that: (1) $\text{AlCl}_3 \cdot i\text{Pr}_2\text{O}$ complexes were the key component that stabilized carbenium ions; (2) $\text{AlCl}_3 \cdot \text{Et}_2\text{O}$ complexes were the key component that promoted proton elimination; and (3) free Et_2O had a negative effect on isomerization and should be removed to the extent possible. This new strategy may provide an alternative to commercial BF_3 -based initiating systems and lead to commercial interest in HRPIB synthesis in pure green



solvent. In addition, the new method can potentially be extended to other initiation systems containing solid Lewis acids.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

- K. Kunal, M. Paluch, C. M. Roland, J. E. Puskas, Y. Chen and A. P. Sokolov, *J. Polym. Sci., Part B: Polym. Phys.*, 2008, **46**, 1390–1399.
- G. K. J. E. Puskas, in *Encyclopedia of Polymer Science and Technology*, Wiley-InterScience, New York, 2003, vol. 5, pp. 382–418.
- J. P. Kennedy and B. Ivan, *Theory and Practice*, Hanser, Munich, Germany, 1991, pp. 173–177.
- B. Giese, *Bunsen-Ges. Phys. Chem., Ber.*, 1983, **87**, 289.
- S. Rach and F. Kühn, *Sustainability*, 2009, **1**, 35–42.
- I. V. Vasilenko, D. I. Shiman and S. V. Kostjuk, *Polym. Chem.*, 2014, **5**, 3855–3866.
- R. Kumar, P. Dimitrov, K. J. Bartelson, J. Emert and R. Faust, *Macromolecules*, 2012, **45**, 8598–8603.
- Q. Liu, Y. Wu, P. Yan, Y. Zhang and R. Xu, *Macromolecules*, 2011, **44**, 1866–1875.
- P. Dimitrov, J. Emert and R. Faust, *Macromolecules*, 2012, **45**, 3318–3325.
- H. Mach and P. Rath, *Lubr. Sci.*, 1999, **11**, 175–185.
- J. J. Harrison, C. M. Mijares, M. T. Cheng and J. Hudson, *Macromolecules*, 2002, **35**, 2494–2500.
- A. G. Evans and G. W. Meadows, *J. Polym. Sci.*, 1949, **4**, 359–376.
- L.-b. Zhang, Y.-x. Wu, P. Zhou, G.-y. Wu, W.-t. Yang and D.-s. Yu, *Chin. J. Polym. Sci.*, 2011, **29**, 360–367.
- S. V. Kostjuk, *RSC Adv.*, 2015, **5**, 13125–13144.
- A.-R. Guo, X.-J. Yang, P.-F. Yan and Y.-X. Wu, *J. Polym. Sci., Part A: Polym. Chem.*, 2013, **51**, 4200–4212.
- K. J. Bartelson, P. De, R. Kumar, J. Emert and R. Faust, *Polymer*, 2013, **54**, 4858–4863.
- R. Kumar, J. Emert and R. Faust, *Polym. Bull.*, 2014, **72**, 49–60.
- R. Kumar, P. De, B. Zheng, K.-W. Huang, J. Emert and R. Faust, *Polym. Chem.*, 2015, **6**, 322–329.
- Y. Li, Y. Wu, X. Xu, L. Liang and G. Wu, *J. Polym. Sci., Part A: Polym. Chem.*, 2007, **45**, 3053–3061.
- Y. Li, Y.-x. Wu, L.-h. Liang, Y. Li and G.-y. Wu, *Chin. J. Polym. Sci.*, 2009, **28**, 55–62.
- Q. Liu, Y.-X. Wu, Y. Zhang, P.-F. Yan and R.-W. Xu, *Polymer*, 2010, **51**, 5960–5969.
- I. V. Vasilenko, A. N. Frolov and S. V. Kostjuk, *Macromolecules*, 2010, **43**, 5503–5507.
- I. V. Vasilenko, D. I. Shiman and S. V. Kostjuk, *J. Polym. Sci., Part A: Polym. Chem.*, 2012, **50**, 750–758.
- L. B. Zhang, Y. X. Wu, P. Zhou and R. W. Xu, *Polym. Adv. Technol.*, 2012, **23**, 522–528.
- D. I. Shiman, I. V. Vasilenko and S. V. Kostjuk, *Polymer*, 2013, **54**, 2235–2242.
- S. V. Kostjuk, I. V. Vasilenko, D. I. Shiman, A. N. Frolov and L. V. Gaponik, *Macromol. Symp.*, 2015, **349**, 94–103.
- M. Vierle, Y. Zhang, E. Herdtweck, M. Bohnenpoll, O. Nuyken and F. E. Kuhn, *Angew. Chem., Int. Ed. Engl.*, 2003, **42**, 1307–1310.
- D. I. Shiman, I. V. Vasilenko and S. V. Kostjuk, *J. Polym. Sci., Part A: Polym. Chem.*, 2014, **52**, 2386–2393.
- S. Zhu, Y. C. Lu, K. Wang and G. S. Luo, *RSC Adv.*, 2016, **6**, 9827–9834.
- S. Zhu, K. Wang and Y. Lu, *ACS Omega*, 2018, **3**, 2033–2039.
- S. Zhu, Y. Lu, K. Wang and G. Luo, *RSC Adv.*, 2016, **6**, 97983–97989.
- D. I. Shiman, I. V. Vasilenko and S. V. Kostjuk, *Polymer*, 2016, **99**, 633–641.
- J. W. Akitt, *Prog. Nucl. Magn. Reson. Spectrosc.*, 1989, **21**, 1–149.
- Y. A. Buslaev and S. P. Petrosyants, *Polyhedron*, 1984, **3**, 265–270.
- D. E. O'Reilly, *J. Chem. Phys.*, 1960, **32**, 1007–1012.
- H. Haraguch and S. Fujiwara, *J. Phys. Chem.*, 1969, **73**, 3467–3473.
- D. Chen, K. P. Taylor, Q. Hall and J. M. Kaplan, *Genetics*, 2016, **204**, 1151–1159.
- Y. Wu and G. Wu, *J. Polym. Sci., Part A: Polym. Chem.*, 2002, **40**, 2209–2214.
- M. Givehchi, M. Tardi, A. Polton and P. Sigwalt, *Macromolecules*, 2000, **33**, 710–716.
- K. Matyjaszewski, *Macromol. Symp.*, 1996, **107**, 53–63.
- I. Dimitrov and R. Faust, *Macromolecules*, 2004, **37**, 9753–9760.

