Synthesis and Characterization of Functional Polymers by Living Polymerization Methods

A Thesis

Submitted to the **University of Pune**

In Partial Fulfillment of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

in

CHEMISTRY

by

R. GNANESHWAR

Division of Polymer Science and Engineering

National Chemical Laboratory

PUNE - 411 008

April 2006

TO MY MOTHER

Acknowledgements

First I thank GOD for giving this beautiful life and showing some purpose to achieve something in my life. I am very much thankful to my mother from whom I learnt the art of hard work and patience. I am thankful to my father who taught me how to follow DHARMA.

I am deeply indebted to my Ph.D. guide Dr. S. Sivaram, for bringing the best from me. Many thanks sir. A basic ground of curiosity to do research I got from him when I met him for the first time during his scientific lecture. Throughout eight years of research, I admired his problem-solving potential of research rather than the fascination of new discoveries. I found in him a person of great character and hard worker and above all a good human being. He taught me that learning is a never-ending process and that it is something that is invaluable. I also express my sincere gratitude to Dr (Mrs.) Rama Sivaram, for moral support.

I am very much thankful to Dr. Wadgaonkar for useful chemistry discussions. I am thankful to Dr Baskaran, Dr. Mahesh Kulkarni, for MALDI ToF MS and Professor A.H.E Muller for HPLC analysis of polymers. I am also thankful to Dr. Idage, Dr. Mohandas, Dr. (Mrs.) Garnaik, Dr. Avadhani, Dr. Vernekar and Dr. Saxena for their co-operation. I am also thankful to Dr. Argade for useful discussions on the chemistry of anhydrides. I am thankful to Dr. R.A Kulkarni and Mrs. Deepa Dhoble for making me proficient in handling GPC. I am also thankful to Ms Nilakshi for assistance with HPLC. I am also thankful to Dr. Rajamohanan, Mrs Phalgune, and Dr. Sathe for teaching me techniques of NMR instrument.

I thank Boje Gowda, Nagaprasad, Yanjarappa, Mallikarjuna, Sridhar Reddy, and Dr. Sesha Sainath, for their kind and helping nature. I am also thankful to other Telugu gang, namely, Uma Shankar, Suresha, Prakash Reddy, Srinivasa Naidu, Suresh, Sunil, Srinivas, Swaroop, Praveen, Raghunadh Reddy, Bhargava Reddy, Sathyanarayana Reddy, Prasad, Nooka Raju and others for their constant support.

I must thank my lab mates Anuj mittal, Mahua, Sandhya, Arun, Neeta, Snehalatha, Smitha and Sony, for their co-operation. I am very much thankful to my friends, Deenadayalan, Rajkumar Patel, Devaraj and their spouse for their constant moral support. I

wish to thank my earlier roommates Laxma Reddy, Srikanth and Sathyanarayana Reddy for their good company. I am fortunate to have timely help from administrative officer, Shri Vidyanathan, Paul Desouza, Security officer Ponkshe, Dr. Kelkar, Dr. R. C. Sharangpani, and Dr. Shashank Sha.

My special thanks to Murugaiah, Srinivas Hotha, Krishnakanth Reddy and Raman Vyasabhattar for their prompt help, for useful chemistry discussions and making me to realize about the world we live in. With them, life at the institute was never boring. Many thanks to them for being good with me always. Also many of this institute is close to my heart for their support. I am also very much thankful to NCL friends Maneesha Barve, Murugan, Bhushan and Jayanth Khandhare for being good with me always.

I am sincerely thankful to my long time friends Shekhar, Pardhasardahi, Ramesh, Mahendhar, Deepa Nair, Swapna and Sridevi for their constant love and wish to achieve something in my life. I would also like thanking all my brothers' late Yadagiri goud, Mallesh goud, Krishna Swamy, late Ella goud, late Venkateshwar goud, Sathyanarayana goud and Mallesham goud and all my sister-in-laws and their children for their co-operation. I am also thankful to two of my sisters and brother-in-laws D. Chandrakala and D. Khistaiah and B. Swarna latha and late B. Narsimha goud. All these family members wished me to achieve something high in my life.

My wife Shailaja came at important stage of my life and gave me moral boost to win against odds. 'Shailu' and my daughter 'Amshu' is GOD's gift to me and always inspired me. I am always thankful to my in-laws Anjaiah Goud and Rajamani, brother in-laws Venumadhav, Pramod and Sudheera and Shivaranjani, for their invaluable support and encouragement. I would like to thank whoever has been deciding my fate for the past thirty five years, because I have no idea how one could have all that I have without being blessed or extremely lucky.

Finally I thank CSIR for the senior research fellowship and the Director, NCL for allowing me to carry out my doctoral research work in this world-class institute.

14-04-2006, Pune (R. Gnaneshwar)

Declaration

I hereby declare that the thesis **"Synthesis and Characterization of Functional Polymers by Living Polymerization Methods"** has not been submitted to any other institute or University for any other degree or diploma and this work was carried out at National Chemical Laboratory, Pune.

(R. Gnaneshwar)

Place: Pune

Date: 14-04-2006

Certificate

The research work presented in this thesis entitled **"Synthesis and Characterization of Functional Polymers by Living Polymerization Methods"** has been carried out under my supervision and is bonafide work of **Mr. R. Gnaneshwar**.This work is original and has not been submitted for any other degree or diploma of this or any other University.

Place:

Date: 14-04-2006

(Dr. S. Sivaram)

(Research Guide)

Contents

Chapter 7: Summary and Conclusions

Synthesis and Characterization of Functional Polymers by Living Polymerization Methods

Abstract

Living/controlled polymerization techniques are expected to proceed in the absence of irreversible chain transfer and chain termination reactions. Therefore, they are powerful tools for the synthesis of diverse macromolecular architectures exhibiting different properties and functions. Controlled polymerization of meth (acrylate) s can be conveniently carried out at or above room temperature using group transfer polymerization (GTP) is a useful technique to synthesize well-defined random, block copolymers including amphiphilic block copolymers containing poly methyacrylic acid segments by using protected monomers, graft, star-branched polymers, networks, functional polymers, macromonomers, telechelics and hyper-branched methacrylates. However, relatively lesser attention has been paid to the possibility of using GTP method to synthesize end functional poly (alkyl methacrylate) s by 'termination method'. Also, the issue of reactivity of GTP 'living' chain ends towards electrophilic termination agents has not been adequately addressed. Hydroxyl, bromine, amine end-functional and a styryl ended macromonomer of poly (methyl methacrylate) s are reported by terminating the living GTP chain-ends of PMMA with benzaldehyde, bromine, methyl E-3-(2-dimethylaminophenyl)-2-phenylacrylate, and with 4-(bromomethyl) styrene respectively. However, all these functionalization reactions have not been adequately characterized for general utility. The objective of the present study is to examine the efficiency of functionalization reaction of silylketeneacetal ended poly (methyl methacrylate) s with various electrophiles. Each functionalization/end-capping reaction is unique and required specific reaction conditions to obtain the best functionalization efficiency.

- Hydroxyl terminated poly (methyl methacrylate) s was synthesized via GTP by terminating silylketeneacetal ended PMMA with benzaldehyde using tetra-n-butyl ammonium bibenzoate (TBABB) catalyst. It was found that 0.1mol% TBABB catalyst concentration is sufficient to obtain high number average degree of functionality (F_n) in the range of 0.70-0.80. MALDI-ToF-MS studies show that the termination of chain ends competes with chain end cyclization, a well-known chain termination reaction in GTP.

- Lactone-end capped poly (methyl methacrylate) s has been prepared via GTP by terminating silylketeneacetal ended PMMA with 5, 6-dihydro-2H-pyran-2-one using 0.1 mol% TBABB catalyst at room temperature. Polymers with F_n in the range of 0.70-0.85 could be obtained. Heterogeneity of end functional group is observed in formed polymers as a result of competing chain end cyclization.

- Amine-terminated poly (methyl methacrylate) s was prepared via GTP by the functionalization reaction of the silylketeneacetal ended PMMA with N-trimethylsilyl benzaldehyde using 1 equivalent of ZnI_2 as catalyst at room temperature. F_n values in the range of 0.80-0.85 were obtained.

- Model reactions between [1-methoxy-2 methyl-1-propenyl)-oxy] trimethylsilane (MTS) with various unsaturated anhydrides namely, itaconic anhydride, citraconic anhydride, maleic anhydride, and 2,3-dimetylmaleic anhydride were carried out under different conditions with a view to establish the feasibility of preparing anhydride-terminated poly (methyl methacrylate) s. $Yb(OTf)_3/CH_2Cl_2$ catalyst gave 1,4 adduct of MTS with itaconic anhydride. However, CH_2Cl_2 is a poor solvent for GTP.

ABBREVIATIONS

ATRA	Atom transfer radical addition
ATRP	Atom transfer radical polymerization
n-BuLi	*n*-butyl lithium
CaH_2	Calcium hydride
CCT	Catalytic chain transfer
CuBr	Copper (I) bromide
CuOAc	Copper acetate
DNbpy	4,4'-di(n-nonyl)-2,2'-bipyridine
DP	Degree of polymerization
DMSO	Dimethylsulfoxide
DNBP	4,4'-di-(5-nonyl)-2,2'-bipyridine
DP	2,2'-dipyridine
DSC	Differential scanning calorimetry
EBI	Ethyl-2-bromoisobutyrate
GC	Gas chromatography
GPC	Gel permeation chromatography
GTP	Group transfer polymerization
HEA	2-Hydroxyethyl acrylate
LAP	Living anionic polymerization
LiCl	Lithium chloride
$LiClO_4$	Lithium perchlorate
LMA	Lauryl methacrylate
MA	Methyl acrylate
MMA	Methyl methacrylate
MTS	(1-Methoxy-2-methyl-1-propenoxy) trimethylsilane
M_n	Number average molecular weight
M_w	Weight average molecular weight
MWD	Molecular weight distribution, M_w/M_n

MW	Molecular weight
PBMA	Poly (butyl methacrylate)
PDT	N, N', N', N", N"-pentamethyl diethylenetriamine
PMA	Poly (methyl acrylate)
PMMA	Poly (methyl methacrylate)
RAFT	Reversible addition fragmentation chain-transfer polymerization
SEC	Size exclusion chromatography
SFRP	Stable free radical polymerization
T_g	Glass transition temperature
TASF	Tris(dimehtylamino)sulfonium difluorotrimethylsiliconate
$TASHF_2$	Tris(dimehtylamino)sulfonium bifluoride
TBABB	Tetra-n-butyl ammonium bibenzoate
TBAF	Tetra-n-butyl ammonium flouride
TEA	Triethyl aluminum
THF	Tetrahydrofuran
TIBAL	Tri isobutyl aluminum
TMA	Trimethyl aluminum
TMEDA	N,N,N',N'-tetramethylethylenediamine

List of Tables

List of Figures

List of Schemes

CHAPTER 2: GENERAL EXPERIMENTAL PROCEDURE

The experimental and characterization methods used in the course of this work are described below.

2.1 Methods of purification

Manipulations like transfer of catalyst, and other moisture/air sensitive reagents was carried out in mBRAUN lab master 100 inert atmosphere glove box.

2.1.1. Nitrogen or argon gas

Nitrogen generator (Dominick Hunter, England, NITROX lab nitrogen generator) model NG 450-1, 230 V, (50 Hz generator) or nitrogen gas cylinder (purity 99.999%, INOX, Mumbai) was used for the bench top inert atmosphere techniques. Following purification methods were employed to remove moisture and oxygen from nitrogen.

The pressurized nitrogen was passed through activated 4 A^o molecular sieves to remove moisture. Oxygen was removed by passing the gas through a copper catalyst at 200 °C. The set up for this purification contains five towers (1m × 3") (Fig. 2.1). The first and third towers contain 4 A^o molecular sieves and the second and fourth contain copper catalyst with the fifth tower containing 5 A^o molecular sieves. After passing nitrogen gas through these towers it was passed through successive beds of anhydrous phosphorous pentoxide and calcium hydride. Finally the gas was passed through a trap of eight cylinders containing toluene solution of oligo-styryl lithium, which removes the last traces of moisture and oxygen besides acting as an indicator for the nitrogen purity.

The copper catalyst and molecular sieves were activated at regular intervals. For reactivating the copper catalyst, hydrogen gas was passed through the towers at 200 °C for 8-10 hours and then the water formed was removed by applying vacuum.

The molecular sieves were reactivated by heating the column (at 200 °C) under reduced pressure for approximately 10 hours. The activated copper catalyst is dark brown in color

while the catalyst before activation is pale green in color. This acts as the visual indicator for determining the appropriate time for reactivation.

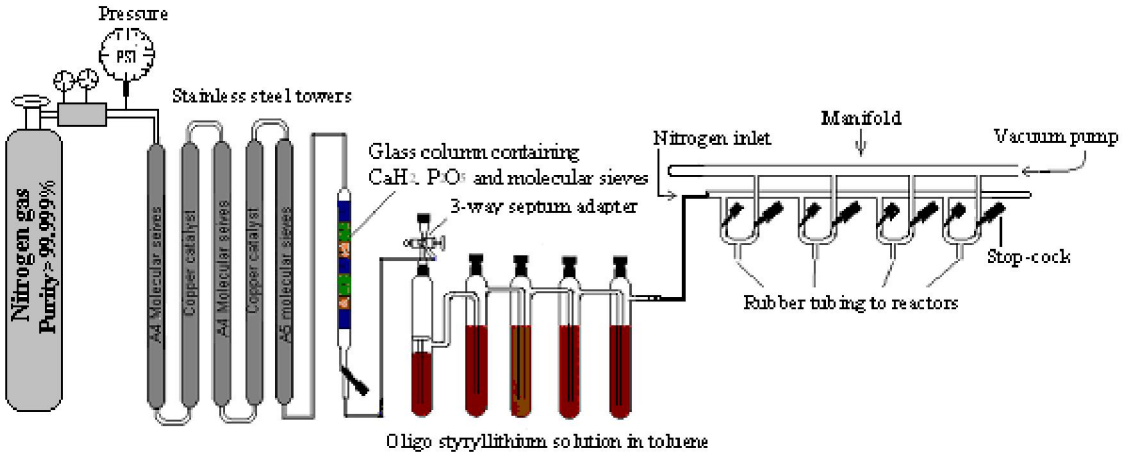


Fig 2.1 Laboratory-scale setup for polymerization under inert atmosphere

A double stage rotary pump was used to evacuate the vacuum line. An oil filter and a cold trap (liquid N_2) prevent oil vapor from entering the manifold as well as organic and water vapors from entering the vacuum pump. The pressure was measured using digital high-pressure Pirani gauge model-DHPG 101 S in the range from atmospheric pressure to 0.001 m. bar. The working pressure of the system is approximately 0.03 m. bar.

The outlets of the vacuum and the dry nitrogen part of the manifold were closed by stopcocks and are connected as shown in Fig 2.1. Different parts of the glassware (reactors, flasks and others) were connected to the outlets by butyl rubber tubing.

2.1.2. Solvents

Solvents used in the present work (THF and toluene) were first subjected to fractional distillation using a 1.5 m column. The fractionated solvents were then distilled over calcium hydride after refluxing over night using a Dean-Stark type distillation unit. This was followed by distillation over sodium-benzophenone complex before distilling them over toluene solution of polystyryllithium in inert atmosphere prior to the polymerization by freeze-thaw method

using the apparatus shown in Fig 2.2. Dichloromethane was stirred over CaH_2 for eight hours and distilled under reduced pressure prior to reaction. The solvents used for precipitation of polymers (methanol and hexane) used after simple distillation. All the solvents were transferred into the reactor using stainless steel capillary (canula) through a rubber septum under a positive pressure of nitrogen.

2.1.3. Monomer

Methyl methacrylate (MMA) was purchased from Aldrich, USA and was stirred over CaH_2 for 5 h, fractionally distilled and finally distilled under reduced pressure. The distilled monomer was stored at 5-10 °C under positive pressure of nitrogen. The required amount of pre-distilled monomer was again purified by distillation, over tri-isobutyl aluminum (TIBAL), using freeze-thaw technique using the apparatus shown in Fig 2.2.

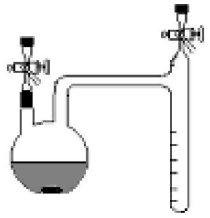


Fig 2.2 Flash distillation apparatus for solvent and monomer distillation

MMA was taken into the distillation unit and a 1.0 M solution of TIBAL in toluene (Schering AG, Germany) was added drop-wise until persistent greenish yellow color complex appears. The bright greenish-yellow color represents the formation of a complex of TIBAL with carbonyl group of MMA and acts as an indicator for monomer purity[1]. The pure monomer was then condensed into the side arm of the monomer purification assembly using liquid nitrogen by freeze-thaw method. Finally MMA was transferred into the dropping funnel by a cannula or syringe.

2.1.4. Initiator

GTP initiator (1-Methoxy-2-methyl-1-propenoxy) trimethyl silane (MTS) (95%, Aldrich, USA) was freshly distilled (bp 35^oC/15 mmHg) prior to use.

2.1.5. Catalyst

Tetra-n-butylammonium bibenzoate (TBABB)

Tetra-n-butylammonium bibenzoate (TBABB) was prepared according to reported procedure[2]. To a separatory funnel was added 10.0 g (0.082 mol) of benzoic acid and 80 mL of 40% aqueous tetra-n-butylammonium hydroxide (TBAOH). The mixture was shaken until homogeneous reaction mixture is obtained and then extracted with 3 x 50 mL of CH_2Cl_2. To the combined extracts was added 10.0 g of benzoic acid and the solution was dried over $MgSO_4$, filter and stripped. The residual solid was dissolved in 250 mL of warm THF and the volume was reduced to 125 mL under aspirator pressure. To the partly crystallizing mixture was added 250 mL ether (in parts) and the mixture was allowed to stand overnight. The product was filtered, washed with ether and dried under vacuum; mp 101-103^oC (lit[2] mp 102^oC). The dried catalyst powder was stored in a round bottom flask under vacuum until use.

2.1.6. Glassware

Cannula and glassware including polymerization reactor were dried in an oven at 130^oC overnight prior to use. The glassware was assembled while hot and flame dried under dynamic vacuum and cooled under nitrogen.

2.2. General procedure for end functional poly (methyl methacrylate) via group transfer polymerization (M_n (theory) = 2000 g/mol)

Group-transfer polymerization of methyl methacrylate (MMA) (M_n (theory) = 2000 g/mol) was carried out on a bench top two-neck reactor equipped with a three-way septum adapter and a dropping funnel fitted with a rubber septum (Fig. 2.3).

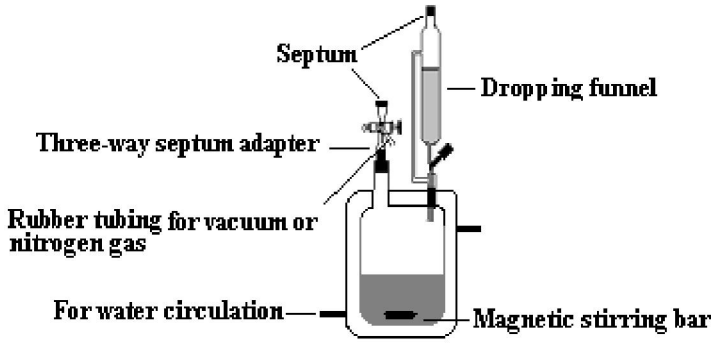


Fig 2.3 Bench-top reactor for group-transfer polymerization

TBABB in THF (1 mL), (0.1mole% based on initiator MTS, $2.35x10^{-6}$ mol) was transferred to the reactor, which was immediately purged with dry nitrogen. Dry solvent THF (30 mL) was transferred via cannula. The desired amount of MTS ($2.35x10^{-3}$ mol) was added to the flask using a microsyringe and the reaction mixture was stirred well, allowing sufficient time (5 minutes) for initiator and catalyst to form a complex. MMA (5 mL, 0.047 mol) was added drop wise via dropping funnel while stirring was continued. Polymerization was continued for 30 minutes and pick out was taken using a syringe and immediately terminated with methanol. To the remaining polymerization solution, a suitable electrophile or Michael acceptor (1 equivalent to MTS) was added and reacted for 12 h at room temperature. Desilylation was accomplished by adding TBAF (1.0 M in THF, 1 equivalent to MTS) at room temperature for 2-3 h.

Finally the polymer solution was poured drop-wise with stirring into n-hexane. The precipitate was filtered and dried under vacuum for 5 - 8 hours at 25 °C to give end-functional PMMA. The yields were generally quantitative.

2.3. General methods of characterization

(a) Nuclear magnetic resonance spectroscopy (NMR)

NMR spectra of functional polymers in $CDCl_3$, acetone-d_6 or CD_3CN (Aldrich) were recorded using a Bruker DRX 500 MHz NMR spectrometer and 5 mm diameter tubes at room temperature. For quantification of functionalization, the functional polymer concentration of 30 mg/mL was used and relaxation delay time of 15 sec with 2000 scans. Functionalization efficiency of end-functional polymers were measured by calculating area of peak corresponds to $–OCH_3$ of PMMA and end-group protons.

(b) Fourier transform infrared spectroscopy (FTIR)

FT-IR spectra of organic compounds and functional polymers were recorded on Perkin Elmer 16PC FT-IR spectrophotometer.

(c) Gas chromatography (GC)

The conversion of an electrophile was determined by using gas chromatography (Perkin Elmer auto-system nelson 1022 XL) by calculating the disappearance of an elctrophile with respect to an internal standard (biphenyl). BP 1 capillary column (SGE, Australia) (dimethyl Polysiloxanes stationary phase), (25m length, film thickness 0.1micron, I.D: 0.22mm) was used with Split 1:60, Sample size: 0.5µL and using FID Detector. Oven temp: 50-200-300^{o}C, ramp rate 10 and 20^{o} C/min; Injector temp: 320^{o}C, Detector temp: 340^{o}C. Response factor R_f of benzaldehyde was calculated as R_f = 1.9015 using biphenyl as internal standard.

(d) Gel permeation chromatography (GPC)

Molecular weight and molecular weight distribution of the end-functional PMMA were determined from SEC (Thermo separation products) equipped with spectra series UV 100 and spectra system RI 150 detectors and Spectra Series P100 pump was used with auto sampler: Spectra Series AS 300. Linear PMMA standards (Polymer Laboratories, M_n = 402 g/mol to 833000 g/mol., M_w/M_n = 1.01 – 1.20) were used for calibration of the column. Two 60 cm PSS SDV-gel columns 1 × linear (10^2 – 10^5 A^{o}) and: 1 × 100 A^{o} with 10 µ at 25^{o}C. The sample concentration was c = 2 mg /mL and the injection volume was 50 µL. HPLC grade THF was used as eluent at room temperature with a flow rate of 1 mL / min.

(e) Vapor pressure osmametry (VPO)

The molecular weights of end-functional polymers were determined by vapor pressure osmametry (VPO) (Knauer, K-7000) using HPLC grade $CHCl_3$ at 35 + 3 ^{o}C with a gain of 032. K_{cal} was found as 22,900 by using benzyl as standard.

(f) High Performance liquid chromatography (HPLC)

Purity of model compounds were determined by HPLC (Waters) at ambient temperature using Zorbax C8 column (USL 0028089) 4.6 mm ID x 25 cm with 2410 RI and 996 UV detector. Mobile phase is methanol. Injection volume is 60 uL and 717 plus auto sampler was used. A 515 HPLC pump was used with a flow rate of 1 mL/minute.

For hydroxyl end functional PMMA, Waters HPLC was used under "Liquid Adsorption Chromatography under Critical Conditions" (LACCC). The conditions were: TSP P4000 pump at 0.5 ml/min, 10 microliter injection volume, TSP UV3000 UV detector, PL EMD 960 Evaporative Light Scattering detector. Eluent THF: hexane 81:19 by weight; at a temperature of 35 °C; Column set: 25 cm x 4 mm, Si 5 µm, Nucleosil 100 A^0 and 300 A^0. For calibration linear PMMA standards from Polymer Laboratory were used.

(g) Matrix assisted laser desorption ionization time of flight mass spectroscopy (MALDI–ToF-MS)

MALDI ToF-spectra were recorded with an Applied Biosystems Voyager-DE STR MALDI ToF spectrometer equipped with 2 m linear and 3 m reflector flight tubes and a 337 nm nitrogen laser (3 ns pulse). Mass spectra were recorded at an accelerating potential of 20 kV in positive ion linear or reflectron mode. Dithranol or 2, 5-Dihydroxybenzoic acid (10 mg/mL THF) was used as a matrix and a small amount of LiCl was used to promote the ionization. Polymer was dissolved in THF (3 mg/mL THF). A PMMA standard with a molecular weight of 4910 g/mol (3 mg/mL THF) was used for calibration, with 2, 5-dihydroxybenzoic acid as matrix (10 mg/mL THF) and with Li cation.

2.4. References

1. Allen, R. D.; McGrath, J. E. *Polym. Bull.* **1986**, 15, 127.

2. Dicker, I. B.; Cohen, G. M.; Farnham, W. B.; Hertler, W. R.; Lagnis E. D.; Sogah, D. Y. *Macromolecules*, **1990**, 23, 4034.

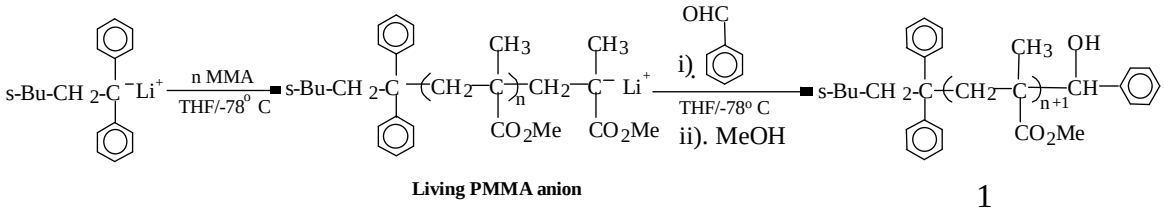
Chapter 3: Synthesis and Characterization of Hydroxyl-Terminated Poly (methyl methacrylate) s via Group-Transfer Polymerization

3.1 Introduction

Group transfer polymerization (GTP) is an attractive method to synthesize a variety of homo, co-polymers, star-branched poly (alkyl methacrylate) s, and functional polymers at room temperature[1]. Living anionic polymerization works better at very low temperature (-78^{o}C) where as GTP works at ambient or elevated temperatures. The 'living nature' of GTP depends on the nature and concentration of catalyst possibly because of the participation of enolate anions in the propagation. Several kinetic and mechanistic studies convincingly suggest that the nucleophile catalyzed GTP of alkyl (meth) acrylate is merely a hypervalent silicon mediated anionic polymerization[2].

End functionalized poly (methyl methacrylate) s (PMMA's) can be synthesized either by atom transfer polymerization (ATRP),[3] by living anionic polymerization (LAP)[4] or via GTP[5]. In general, two approaches are possible, viz, use of functional initiators or termination of the "living" chain by a suitable electrophile (or radical precursors) bearing the functional groups. Either of the methods have both merits and demerits. For example, functional initiators having active hydrogen groups (-OH, -NH_2) cannot be directly used in LAP and GTP and will require a protection-deprotection sequence. For example, [(2-methyl-1-[2-(trimethylsiloxy)ethoxy]-1-propenyl)oxy] trimethylsilane was used as initiator for MMA polymerization via GTP which gives quantitatively α-OH functional PMMA upon deprotection of the end group[6]. Hydroxyl end-functional polymers have been prepared via LAP by Andrews and coworkers via a complex functional initiator formed from a hydroxyl protected alkyl lithium and diphenylethylene[7].

In another approach, direct reaction of polymeric organolithium compound with ethylene oxide produces the corresponding hydroxyethylated polymer in quantitative yield without any significant formation of oligomeric ethylene oxide block[8]. Smith[9] reported the use of benzaldehyde as an electrophilic terminating agent for the synthesis of ω-hydroxyl-terminated PMMA (**1**) by LAP. The low reactivity of the methacrylate anion could be circumvented with an appropriate reaction design. Termination of the growing methacrylate anion (derived from diphenylhexyllthium) with benzaldehyde in THF at -78°C results, after hydrolysis, in benzhydryl alcohol end-functional PMMA (Scheme 3.1).



Living PMMA anion 1

Scheme 3.1. Benzhydryl alcohol terminated PMMA by LAP

Use of functional initiator without protection is possible in ATRP. Haddleton reported[10] the ATRP of MMA with a pyridinecarbaldehyde imine copper (I) catalyst and hydroxyl functional alkyl bromide initiator (2-hydroxyethyl 2'-methyl-2'-bromopropionate), which leads to α-hydroxyl functional PMMA with controlled M_n in the range 2500 to 20 000 g/mol and M_w/M_n < 1.2.

The Mukaiyama aldol reaction between silyl ketene acetals (or silyl enol ethers) and aldehyde provides a synthetic route for β–hydroxyl carbonyl compounds via carbon-carbon bond formation. Since its discovery promoted by Lewis acid catalyst, namely, $TiCl_4$[11], a variety of catalysts such as trityl salts[12(a)], transition metal salts[12(b)], silver (I) carboxylate-bis (phosphine) [12(c)], rhodium (I)-diphosphine complexes[12(d)], Et_2O: MgI_2[12(e)], $AlMe_2Cl$[12(f)], Ru (salen)(NO)(H_2O)] SbF_6[12(g)] $BF_3.OEt_2$, $LiClO_4$, $Yb(OTf)_3$, $Sn(OTf)_2$, $Zn(OTf)_2$ [12(h)] 1,8-diazabicyclo [5.4.0] undec-7-ene (DBU)[12(i)], SmI_2[12(j)], and iodine [12(k)] have been used as catalysts for this reaction. None of the above catalysts, however, are effective in a strongly

coordinating solvent, such as, THF. Typical solvent for Mukaiyama aldol reaction is methylene chloride.

Mukaiyama aldol reaction using MTS with benzaldehyde is also reported in ionic liquids[12(l)], high pressure[12(m)], elevated temperature[12(n)] (150^{o}C) (in the absence of solvent), in solvent assisted[12(o)] (in DMSO) process and lanthanide fluorous catalyst (lanthanide bis (perfluorooctanesulfonyl) amide)[12(p)]. However, none of these conditions are suitable for the functionalization reaction of silyl ketene acetal ended PMMA with benzaldehyde.

A highly nucleophilic phosphine, namely, tris (2, 4, 6-trimethoxyphenyl) phosphine (TTMPP) catalyzes the aldol reaction between MTS and benzaldehyde to give the corresponding aldol product in good yields (89%) in THF at room temperature. This reaction is considered to proceed through naked enolates produced by nucleophilic O-Si and C-Si bond cleavage[13].

Sogah reported[14] the use of nucleophilic catalyst tris (dimehtylamino) sulfonium bifluoride ($TASHF_2$) (5 mol% based on MTS) for the reaction of MTS and benzaldehyde to yield the aldol adduct in > 95% at ambient temperature in THF. Webster and coworkers[15] then extended this reaction to the termination of silyl ketene acetal-ended PMMA with benzaldehyde using $TASHF_2$ catalyst to give, after desilylation using TBAF/MeOH, a PMMA with a terminal benzhydryl alcohol group.

In this chapter we describe a detailed examination of the electrophilic termination reaction of silyl ketene acetal ended PMMA (prepared with TBABB catalyst in THF at 25^{o}C using MTS as initiator) with benzaldehyde using a weakly nucleophilic TBABB as catalyst in THF at 25^{o}C. The efficiency of polymer functionalization was examined using ^{1}H NMR, SEC and MALDI-ToF methods. Weakly nucleophilic TBABB is reported to be a superior catalyst for GTP conferring on the reaction enhanced livingness and reduced chain termination.

3.2 Experimental Methods

3.2.1 Materials

Benzaldehyde (Merck, India) was washed with $NaHCO_3$ solution, and dried over Na_2SO_4, finally fractional distilled under vacuum (62^oC/10mm Hg) and stored under nitrogen. Cp_2TiCl_2, Cp_2ZrCl_2, $Yb(OTf)_3$ (97%, Aldrich, USA) were dried at 30^oC and $LiClO_4$ at 150^oC under dynamic vacuum for 18 hours before use.

3.2.2 Model reaction of MTS with benzaldehyde

A flame dried two neck flask, equipped with a nitrogen inlet, a three way septum adapter, and a dropping funnel (fig 2.3, chapter-2) was charged with 0.150 grams of biphenyl (internal standard) ($9.73x10^{-4}$mol), TBABB (0.1mol% of MTS), 30 mL of THF using a canula under positive pressure of nitrogen and 1.0 mL (0.005 mol) of MTS using a syringe at 30^oC. After 5 minutes, 0.5 mL of benzaldehyde (0.005 mol) was added at once. Every five minutes pick outs were taken and analyzed by gas chromatography. Percentage of benzaldehyde conversion was calculated using response factor R_f value of benzaldehyde (R_f value of benzaldehyde was found as **1.9015** using biphenyl as internal standard using BP-1 column), conditions, **BP-1** column, 25m length, film thickness 0.1micron, I.D 0.22mm, carrier gas: N_2, split 1:60, sample size: 0.5µL; detector: FID; oven temperature program:

	Temp(^oC)	Time(min)	Rate
Step 1:	100	5.00	30.0
Step 2:	200	0.00	20.0
Step 3:	300	2.00	0.0

Injector temp : 320^oC
Detector temp : 350^oC
N_2 pressure : 0.4921 kg/cm^2
Attenuation : 16

Desilylation reaction was carried out using THF: 1 N HCl (20:1) at 0^oC. After 0.5 h sat. aq $NaHCO_3$ was added. THF was removed under reduced pressure and product was extracted with CH_2Cl_2. The organic extract was washed with brine and dried (Na_2SO_4). Later, CH_2Cl_2 was removed under reduced pressure and crude product was chromatographed on silica gel to afford methyl 3-hydroxy 2,2 dimethyl-3- phenylpropionate (**4**) in > 95% yield.

^{1}H NMR ($CDCl_3$): 0.97(s, 3H), 1.05 (s, 3H), 3.25 (brs, 1H), 3.52 (s, 3H), 4.72 (s, 1H), 7.06-7.26 (m, 5H)

FT-IR (neat): ν = 3495, 1730 cm^{-1}

Melting Point: 68.5-69.5 (lit[16] mp: 69.5-70.5)

3.2.3 Hydroxyl-end functional poly (methyl methacrylate) s

To a flame dried two neck 250 mL flask, equipped with a nitrogen inlet, and a dropping funnel (fig 2.3, chapter-2) was charged with 1.2 mg of TBABB in THF (1 mL) (0.1mol% of MTS), followed by 30 mL dry THF using a canula under positive pressure of nitrogen and 0.5 mL of MTS ($2.35x10^{-3}$ mol) using a syringe at 25°C. After 5 minutes, 5 mL of MMA (0.047 mol) was added from a dropping funnel at a rate of 1mL/min. The solution was stirred for 30 minutes. An aliquot of 5 mL was withdrawn using a hypodermic syringe under a positive pressure of nitrogen, terminated with methanol and precipitated in n-hexane. The polymer was filtered and dried at 60°C/400 mm Hg. To the remaining reaction mixture, additional amount of TBABB catalyst (0.1mol% of MTS) in 5 mL THF was added, followed by 0.3 mL of benzaldehyde ($2.35x10^{-3}$ mol) and the reaction was allowed to continue for 12 h at 25°C. Subsequently, 3 mL of $2.35x10^{-3}$ mol of NBu_4F/methanol was added to the reaction mixture and the reaction was continued for 2 h at 25°C. The desilylated product was precipitated in n-hexane. The polymer was further purified by reprecipitating it from THF solution using excess hexane and dried at 60°C/400 mm Hg. The polymer yield was quantitative (4.9 g).

3.2.4 Characterization

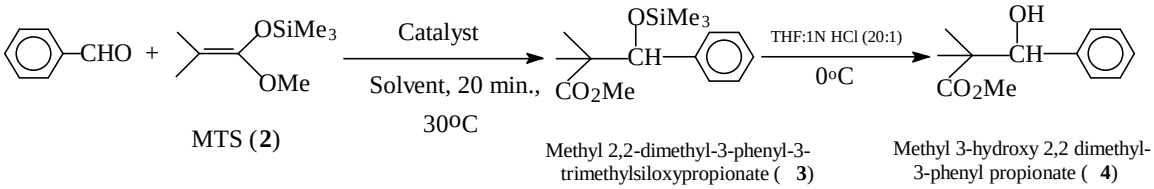
The methods of characterization are described in chapter-2.

3.3 Results and discussion

3.3.1 Reaction between MTS and benzaldehyde

The reaction between benzaldehyde and MTS (Scheme 3.2) using various catalysts in different solvents was carried out at 30°C. The progress of reaction was monitored by determining benzaldehyde conversion using gas chromatography. A minimum of three injections were made to confirm the reproducibility of analysis. Number of moles of benzaldehyde present at a given time was determined using the equation, mole ratio = area ratio x R_f ; moles of benzaldehyde = moles of internal standard (biphenyl) x area ratio x R_f

Catalysis of the Mukaiyama Aldol reaction using various Lewis acids and a nucleophilic catalyst TBABB are shown in table 3.1. Dried $Yb(OTf)_3$ is reported to induce cationic ring-opening polymerization of THF (entry 1, table 3.1).



Scheme 3.2. Reaction of MTS with benzaldehyde

However, Sawamoto and coworkers found that in the presence of 2,6-di-tert-butyl-4-methylpyridine, ring-opening polymerization of THF could be suppressed[17]. The high activity of $Yb(OTf)_3$ even in the presence of a nitrogen base is due to its high Lewis acidity as well as due to the large radius[18] and high co-ordination number of Yb(III).

Table 3.1. Model reactions between MTS and benzaldehyde in the presence of different catalysts and solvent at room temperature

Entry	Catalyst[a]	Solvent	%Conversion of bezaldehyde in 20 min. at 30°C
1	$Yb(OTf)_3$	THF[b]	80
2	$Yb(OTf)_3$	THF: H_2O 4:1	Nil
3	$Yb(OTf)_3$	Toluene	91
4	$Yb(OTf)_3$	CH_2Cl_2	97
5	TBABB 0.1 mol%	THF	98
6	CP_2ZrCl_2 Or CP_2TiCl_2	THF	Nil
7	$LiClO_4$	CH_2Cl_2	85
8	$LiClO_4$	THF	25

a: $Yb(OTf)_3$,Cp_2ZrCl_2 ,Cp_2TiCl_2 and $LiClO_4$ were used in 10 mol% [based on benzaldehyde]
b: Dried $Yb(OTf)_3$ induces cationic ring-opening polymerization of THF

No aldol adduct was obtained when THF:H_2O (4:1) was employed. In aqueous media, hydrolysis of MTS precedes the desired aldol reaction (entry 2, table 3.1). $Yb(OTf)_3$ is stable without hydrolysis or decomposition even in water and it can be reused several times without loss of its activity[19(a)]. Kobayashi reported[19(b)] that $Yb(OTf)_3$ effectively catalyzed the aldol reaction of silyl enol ethers with aldehydes in aqueous media. In other organic solvents such as toluene and dichloromethane (entry 3, 4, table 3.1) $Yb(OTf)_3$ worked well (91, and 97% conversion respectively). Yb salts with less-nucleophilic counter anions (like OTf^- or ClO^-_4) are more cationic and the high Lewis acidity promotes the desired reaction.

Cp_2ZrCl_2 or Cp_2TiCl_2 were not effective Lewis acid catalysts for the model reaction (entry 6, table 3.1). It was reported[20] that 5 mol% of cationic zirconocene complexes $[Cp_2Zr(O^tBu)THF][BPh_4]$ gives 90-95% yield of aldol adduct in dichloromethane at 25°C. High conversion of benzaldehyde was observed with 10-mol% $LiClO_4$ in dichloromethane in spite of the heterogeneous nature of the reaction mixture. On the contrary 10 mol% $LiClO_4$ in THF is homogeneous. Yet only low conversion was observed (entry 7, 8, table 3.1). This is presumably due to the fact that benzaldehyde is in competition with the solvent (THF) for corordination to the lithium cation. Reetz et al. have reported[21] the reaction of MTS with benzaldehyde using 10 mol% $LiClO_4$/diethyl ether resulted in 56% yield of the expected aldol product.

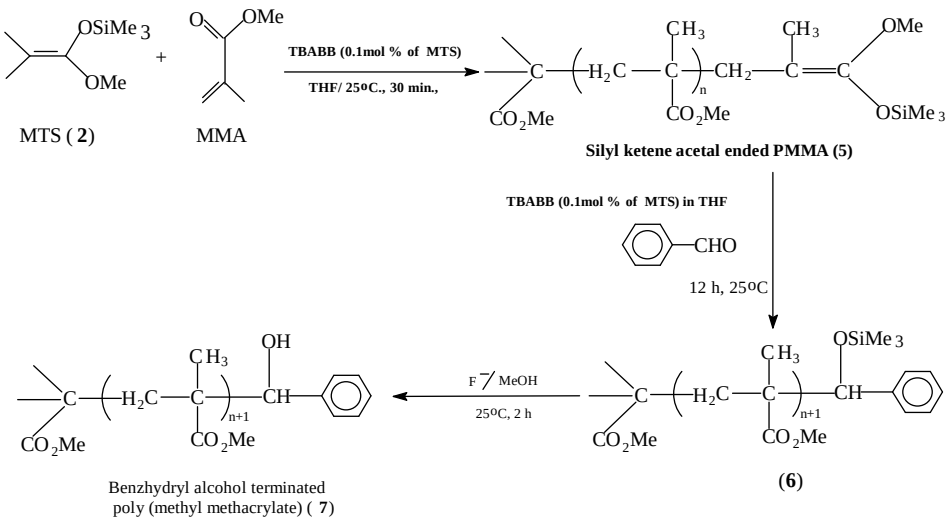
When the product methyl 3-hydroxy 2,2 dimethyl-3- phenylpropionate (**4**) was injected into GC at an injector temperature of 320°C, benzaldehyde and methylisobutyrate were detected. This implies that the secondary benzhydryl alcohol was thermally labile on a basic column (BP-1, polyamide coated). Thermogravimetry analysis (TGA) of methyl 3-hydroxy 2, 2 dimethyl-3- phenylpropionate (**4**) showed an initial degradation at 82.5°C (0.672% wt loss), 50% weight loss at around 173°C and 99.2 %wt loss at 240-245°C. Therefore, the product was analyzed as methyl 2, 2-dimethyl-3-phenyl-3- trimethylsiloxypropionate(**3**).

Model studies establish that reaction between MTS and benzaldehyde is rapid and quantitative using $Yb(OTf)_3$ in CH_2Cl_2 and TBABB in THF. TBABB is easy to prepare, less hygroscopic than other catalysts such as $TASHF_2$ and is soluble in THF. Consequently, TBABB was employed as catalyst for electrophilic termination of GTP chain end by benzaldehyde.

3.3.2 Hydroxyl-terminated PMMA via GTP

MMA polymerization in presence of TBABB catalyst (0.1 mol% based on MTS **2**) in THF (MMA concentration 3.13-1.88 mol/L) was carried out at 25°C. It is reported[22] that less nucleophilic TBABB catalyst gives low cyclic fraction due to backbiting reaction compared to more nucleophilic $TASHF_2$ catalyst. Benzaldehyde was reacted with silyl ketene acetal ended PMMA for 12 h at 25°C (Scheme 3.3). The hydroxyl terminated PMMA (**7**) was purified by reprecipitation of the dilute solution of polymer (5% w/v) into n-hexane. TLC detected no benzaldehyde in the final polymer.

The number average molecular weight (M_n) and molecular weight distribution (M_w/M_n) of the polymers were determined by SEC and are given in table 3.2. The terminal functional group of the obtained polymers was then analyzed by ^1H NMR spectroscopy. Besides the large absorptions of the repeat units of MMA, there are characteristic signals originating from the end group i.e. $OSiMe_3$ and aromatic protons. The DP_n of functional polymer was calculated by using area ratio of OMe vs. aromatic protons (Figure 3.1).



Scheme 3.3. Synthesis of hydroxyl terminal PMMA via GTP

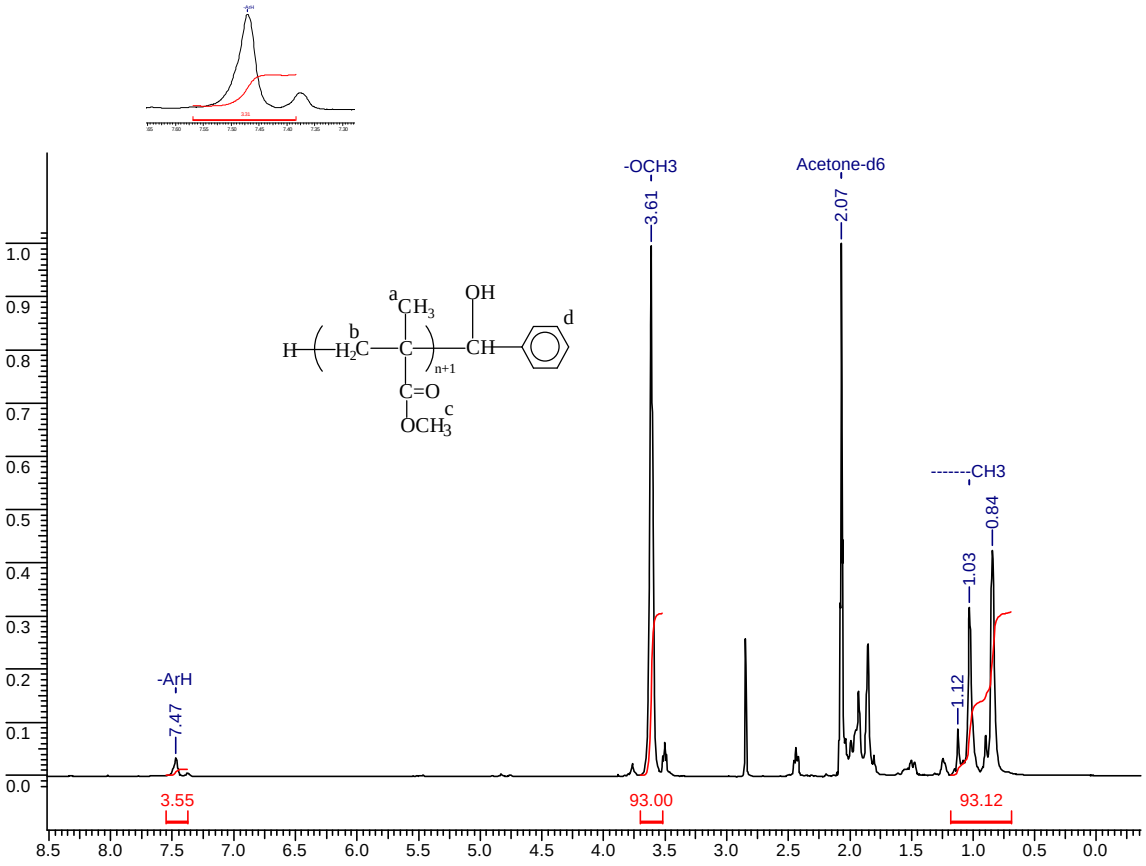


Fig 3.1 ^{1}H NMR spectrum of hydroxyl end-functional PMMA (Entry 9, table 3.2) in acetone-d_6 (500 MHz)

Table 3.2. Synthesis and characterization of hydroxyl terminal PMMA prepared via GTP

Entry. No.	MMA, mol	MTS, mol x10^3	THF, mL	TBABB mol x 10^5	TBABB[a] mol x10^5	Benzal dehyde, mol x 10^3	M_n Theory (g/mol)	M_n (GPC) (RI)	M_w/M_n	M_n (VPO)	Mn (NMR)	$I^e_{efficiency}$	F^f_n
1	0.094	3.28	30	3.28 (1 mol%)	3.28 (1 mol%)	3.28	3200	2890	1.19	2700	3800	1.10	0.76
2	0.094	3.28	30	0.328 (0.1 mol%)	0.328 (0.1 mol%)	3.28	3200	4080	1.14	3900	5120	0.78	0.80
3	0.094	3.28	40	0.328 (0.1 mol%)	0.328 (0.1 mol%)	3.28	3200	3360	1.12	3500	4253	0.95	0.79
4	0.047	1.64	15	0.164 (0.1 mol%)	0.164 (0.1 mol%)	1.64	3200	2990	1.19	3200	4000	1.06	0.75

5	0.047	3.2	15	1.64 (0.5 mol%)	1.64 (0.5 mol%)	3.2	1700	1690	1.19	2000	2750	1.00	0.62
6	0.047	3.28	25	0.328 (0.1 mol%)	0.328 (0.1 mol%)	3.28	1700	2000	1.06	2300	2663	0.85	0.75
7[b]	0.047	1.64	15	1.64 (1 mol%)	No catalyst	1.64	3200	3230	1.18	3500	4500	0.99	0.72
8[c]	0.047	2.35	20	1.15 (0.5 mol%)	No catalyst	2.35	2200	2330	1.07	2000	3100	0.94	0.75

9[d]	0.047	1.64	15	1.64x10^{-5} (1 mol%)	1.64x10^{-5} (1 mol%)	1.64	3200	2915	1.17	3200	4360	1.09	0.67

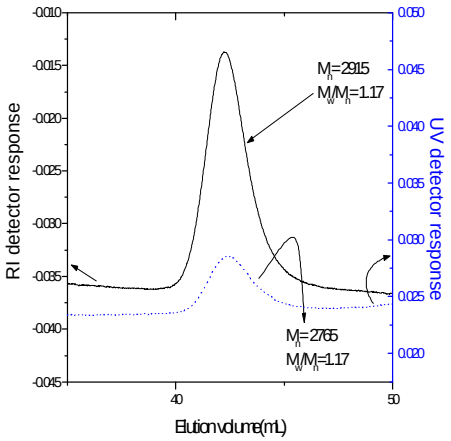
All experiments were carried out at 30^{o}C; For functionalization reaction: [Benzaldehyde]/[MTS] = 1

a: Additional TBABB catalyst added prior to addition of benzaldehyde.

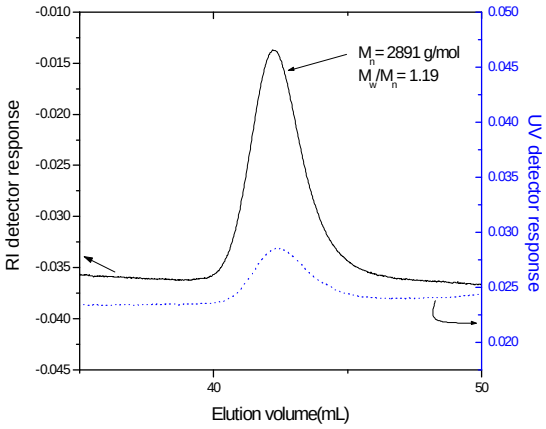
b, c: No additional catalyst was added for functionalization

d: Functionalization reaction was performed at 0^{o}C; **e:** $I_{efficiency} = M_{n\ (theory)}/ M_{n\ (SEC)}$., **f:** $F_n = DP_n$ (SEC) / DP_n(^{1}H NMR)

Initiator efficiency ($I_{efficiency}$) was found to vary between 0.78 to 1.11 depending on MMA and TBABB concentration (table 3.2). The obtained polydispersities were narrow (M_w / M_n 1.06-1.19). The ultraviolet and the refractive index traces in size exclusion chromatography (SEC) were almost identical over the entire molecular weight range (Figure 3.2).



(Entry 9, table 3.2)



(Entry 1, table 3.2)

Figure 3.2. SEC trace of benzhydryl alcohol terminated PMMA, using RI and UV detector

As shown in table 3.2, DP_n's are in agreement with the values obtained from size exclusion chromatography. The number average functionality (F_n) of the functional polymer was determined from DP_n (SEC)/DP_n (^{1}H NMR). The values are less than unity, indicating that competing back-biting reaction occurred along with functionalization reaction.

Reaction conditions such as catalyst concentration and reaction temperature could have an influence on the efficiency of functionalization reaction. Functionalization reaction performed at 0^{o}C did not show any significant improvement over that performed at 25^{o}C (entry 1 and 9, table 3.2). There was no loss of efficiency even when no additional catalyst was added prior to the addition of benzaldehyde. Similarly, increasing MMA concentration had no effect on the efficiency of the reaction.

Webster and coworkers reported[15] MMA polymerization in THF using 1-(2-(trimethylsiloxy) ethoxy)-1-(trimethylsiloxy)-2-methyl-1-propene as initiator and $TASHF_2$ as a catalyst at room temperature and after 2 h, the polymer was terminated with benzaldehyde using additional

$TASHF_2$ catalyst and reacted overnight to get protected hydroxyl PMMA with M_n = 2800, M_w/M_n = 1.04). Comparison of $OSiMe_3$ peak areas with the methacrylate OMe at δ 3.6 gave a OMe: $OSiMe_3$ (incorporated monomer: end group) value of 18.4; theoretical dp of the polymer is 29.4 and monomer/end group is expected to be 14.7. The desilylation with TBAF/MeOH at reflux temperature for 1.5 h, yielded hydroxyl-PMMA with M_n = 3200 g/mol (M_w/M_n = 1.18).

The OH-functionalized GTP polymers were analyzed by liquid adsorption chromatography under critical conditions (LACCC). The silyl ether end functional PMMA (**6**, scheme 3.3) elution volume is shifted by ca. -0.2 mL and the hydrolyzed one i.e. hydroxyl end functional PMMA (**7**, scheme 3.3) back to the original place i.e., at PMMA position (Figure 3.3). The UV signals at 254 nm are bimodal possibly due to inadvertent conversion of PMMA-$OSiMe_3$ to PMMA-OH up on storage.

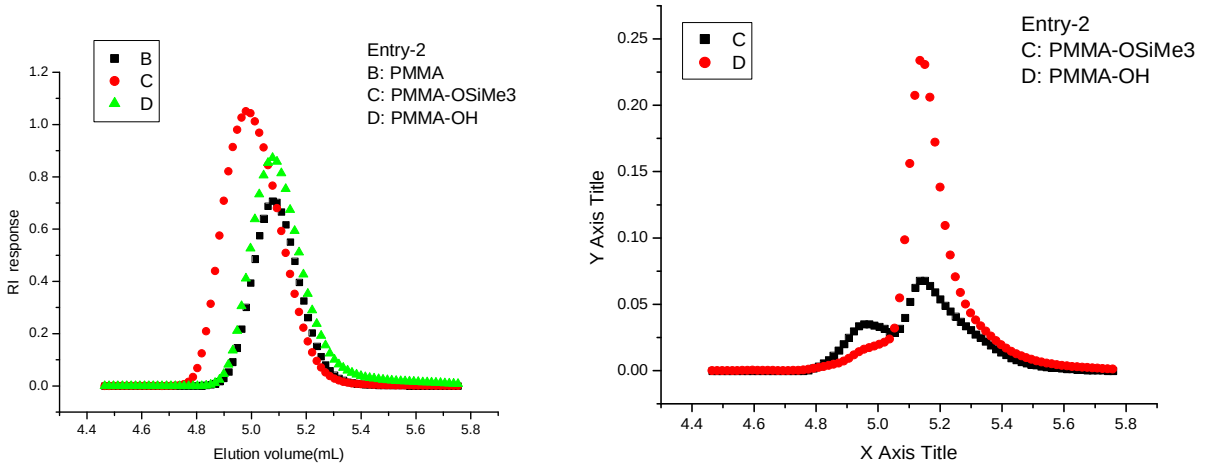


Fig 3.3 HPLC (LACCC) analysis of PMMA, PMMA-$OSiMe_3$, and PMMA-OH using RI and UV detector (entry 2, table 3.2)

The hydroxyl end functional PMMA's prepared by GTP were found to be predominantly syndiotactic (58-60%) (table 3.3) as expected.

Table 3.3. Stereochemistry of hydroxyl end-functional PMMA prepared by GTP

Entry No.	Temp ^oC	M_n RI	M_w/M_n RI	Triads, % mm	mr	rr
1	25	2891	1.19	6.0	36	58

2	25	4077	1.14	4.0	36	60
9[a]	0	2915	1.17	4.0	37	59

a: Functionalization reaction at 0°C

MALDI-ToF-MS of hydroxyl terminated PMMA were performed by dissolving the polymer in THF (3 mg/mL) and mixed 1:1 with the matrix 2,5-dihydroxybenzoic acid (10 mg/mL solution in THF). For enhancement of ion formation, a small amount of LiCl was added to the solution. After depositing 0.5 μL of the solution on the sample holder the solvent was evaporated in hot air. The mass peaks corresponding to the $[M+Li]^+$ molecular ions for hydroxyl end-functional PMMA $\{[M+Li]^+ = 100.12(DP)+H\ (1.0079)+107.1324(C_7H_7O)+Li^+(6.941)\}$ were (expected series), 4104.92, 4205.04, etc. MALDI ToF exhibited major series is 4106.04, 4207.11,…..etc. (with Δ = 2) (fig 3.4, entry 2, table 3.2). No cyclic fraction was observed.

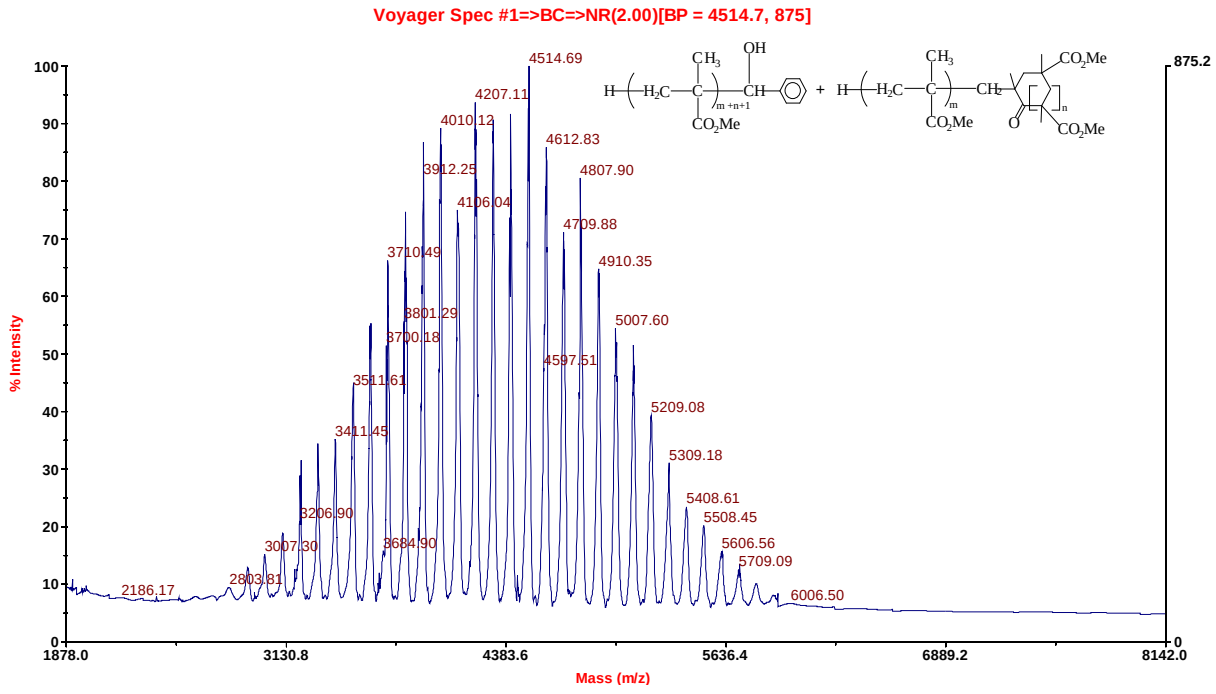


Fig 3.4. MALDI-ToF spectrum of hydroxyl end-functional PMMA prepared by GTP (using 0.1 mol% TBABB catalyst; entry 2, table 3.2). M_n=100.12(20)+H (1.0079)+107.1324(C_7H_7O)+K^+(39.098).(Matrix: Dithranol and CF_3COOK for enhancement of ion formation) (Δ= 6 Da)

This is in accordance with the observation that the living nature of GTP depends on the nature and concentration of catalyst[23] and also on molar mass of the polymer. Here we used 0.1 mol% of a poorly nucleophilic TBABB catalyst to keep the cyclic fraction low.

Figure 3.5 shows MALDI-ToF spectrum of hydroxyl end-functional PMMA (entry 9, table 3.2) in which functionalization reaction carried out at 0°C using 1 mol% TBABB catalyst. M_n=100.12(20)+H(1.0079)+107.1324(C_7H_7O)+Li^+(6.941) i.e. for e.g. n= 30 gives M_n= 3118.6813 g/mol i.e., expected series of major fraction will be 3118.6813, 3218.8013, 3318.9213…….. etc. MALDI ToF exhibited a major series (figure 3.5) as 3104.56, 3204.62, 3304.26…….etc with Δ= 14 Da. Additionally, low intensity peaks attributed to an oligomer series with cyclic end groups [M+Li] $^+$ = 100.12 (MMA) * n (DP) + H (1.0079) - OCH_3 (31) + 6.9(Li) for e.g. n= 30 give M_n =2980.5147 g/mol i.e., series of lower fraction will be 2980.5147, 3080.6347…….etc. were also observed at mass numbers 2977.98, 3077.06……..etc. with Δ= 3 Da.

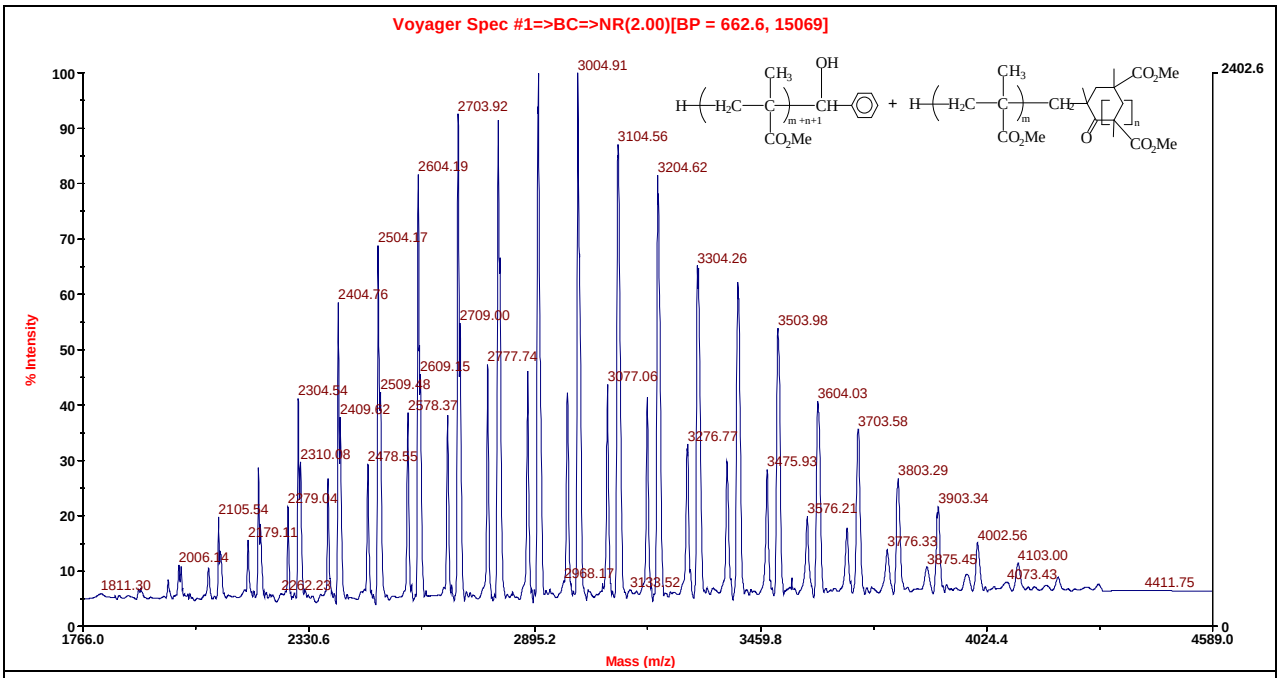
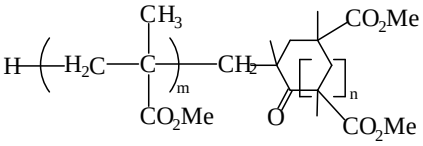
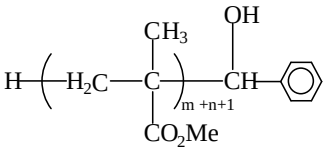


Fig 3.5. MALDI-ToF spectrum of hydroxyl end-functional PMMA prepared by GTP (using 1 mol% TBABB catalyst entry 9, table 3.2). M_n=100.12(20)+H(1.0079)+107.1324(C_7H_7O)+Li^+(6.941) (Matrix: Dihydroxybenzoic acid and LiCl for enhancement of ion formation) (Δ= 14 Da)

Table 3.4.Different observed series in MALDI ToF of hydroxyl end-functional PMMA[a]

prepared by GTP.

Polymer	*Ion*	*End group*	*Observed series*[b]
	Li^+	*Cyclohexanone end group with n =1 i.e. loss of –OCH_3 from linear fraction*	1978.32, 2077.62, 2177.74,etc. with Δ= 2 Da
	Li^+	*107.1324 (C_7H_7O)-hydroxyl end group*	*2010.88, 2110.80, 2210.60 etc. with Δ= 7 Da*

a: Matrix is 2,5-dihydroxybenzoic acid (F.W: 154.13) with Li^+ (LiCl salt)
b: $[M+Li]^+$= 100.12 (DP)+H (1.0079)+107.1324(C_7H_7O)+Li^+(6.941)

Similarly, figure 3.6 shows MALDI-ToF spectrum of hydroxyl end-functional PMMA (entry 8, table 3.2) in which 0.5 mol% TBABB was used for both MMA polymerization and for end-capping reaction with benzaldehyde. Here also the major series is observed as 2010.88, 2110.80, 2210.60……etc. with Δ= 7 Da. Expected major series will be 2017.36, 2117.48, 2217.60… …..etc. The second oligomer series observed due to cyclic fraction is 1978.32, 2077.62, 2177.74,…….etc. with Δ= 2 Da. So, from MALDI ToF analysis, it is observed that 0.1-mol% TBABB catalyst keeps low cyclic fraction. Different observed series in MALDI ToF of hydroxyl end-functional PMMA prepared by GTP is shown in table 3.4.

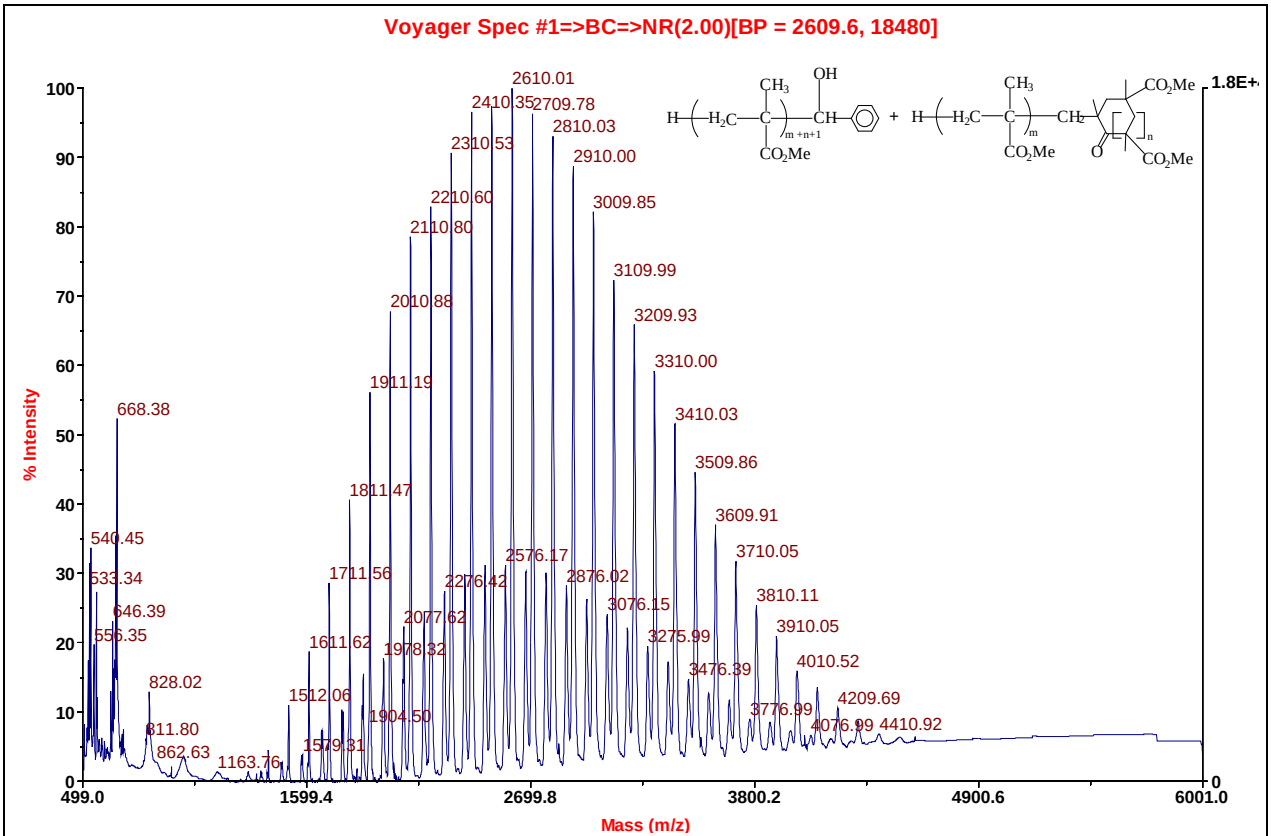


Fig 3.6. MALDI-ToF spectrum of hydroxyl end-functional PMMA prepared by GTP (0.5 mol%, entry 8, table 3.2). M_n=100.12(20)+H (1.0079)+107.1324(C_7H_7O)+Li^+(6.941)(Matrix: Dihydroxybenzoic acid and LiCl for enhancement of ion formation) (Δ= 7 Da)

3.4 Conclusions

Hydroxyl-terminated poly (methyl methacrylate) was prepared via group-transfer polymerization with narrow molecular weight distribution (M_w/M_n = 1.06-1.19) with initiator efficiencies in the range of 0.78-1.10. The number average functionalization efficiency was between 0.70-0.80.

From MALDI ToF studies of hydroxyl-terminated PMMA, it is observed that cyclized chains are formed along with chain growth particularly during or just before functionalization reaction. This also strongly supports dissociative mechanism for GTP in which ester enolates acts as initiator as well as catalyst. It was also found that use of 0.1 mol % TBABB catalyst (based on initiator) and drop wise addition rate of MMA while

keeping monomer concentrations high led to high end-functionality and low cyclic fraction in the polymer.

3.5 References

1. (a). Webster, O.W, Hertler, W.R, Sogah, D.Y, Farnham, W.B, Rajan Babu, T.V. *J Am Chem Soc* **1983,** 105, 5706.

2. Webster, O. W. *Adv. Polym. Sci.* **2004**, 167, 1.

3. Coessens, V.; Pintauer, T.; Matyjaszewski, K *Prog. Polym. Sci.* **2001**, 26, 337.

4. (a). Patil, A.O.; Schulz, D.N.; Novak, B. M. *Functional Polymers*, ACS Symposium series, **1998**, 704. (b). Mahua, G. Ph.D. thesis, **2002**, Pune University, India. (c). Hirao, A.; Hayashi, M.; Loykulnant, S.; Sugiyama, K.; Ryu, S. W.; Haraguchi, N.; Matsuo, A.; Higashihara, T. *Prog. Polym. Sci.* **2005**, 30, 111.

5. (a). Hertler, W. R. *Group transfer polymerization*. In: Kricheldorf, H. R. (ed) *Silicon in polymer synthesis*. **1996** Springer, Berlin Heidelberg New York, p 69.(b). Asami, R.; Kondo, Y.; Takaki, M. *ACS Polymer Preprints* **1986**, 27, 186. (c) Spinelli, H. J. *Adv. Org. Coat. Sci. Technol. Ser* **1990**, 12, 34. (d). Cohen, G. M. *ACS Polymer Preprints* **1988**, 29, 46. (e). Sogah, D. Y.; Webster, O. W. *J. Polym. Soc. Lett. Ed.* **1983**, 21, 927. (f). Quirk, R. P.; Ren, J. *Polymer International* **1993**, 32, 205. (g) Farnham, W. B.; Sogah, D. Y. *US Patent*, 4, 524, 196, **1985.** (h) Farnham, W. B.; Sogah, D. Y. *US Patent*, 4, 414, 372, **1983.** (i) Cohen, G. Mreich, H. J. *US Patent*, 4, 983, 679, **1991**

6. Hertler, W. R.; Sogah, D. Y.; Webster, O. W.; Trost, B. M. *Macromolecules* 1984**, 17, 1415.**

7. Anderson, B.; Andrews, G.; Arthur, P.; Jacobson, H.; Melby, L.; Playtis, A.; Sharkey, W.
***Macromolecules*,** 1981**, 14, 1599.**

8. Ma, J.-J.; Quirk, R. P. *J. Polym. Sci., Part A: Polym. Chem*. 1988**, 26, 2031.**

9. Smith, S. D. *Polym. Prepr.* 1988**, 29, 2, 48.**

10.Shooter, A. J.; Jasieczek, C. B.; Derrick, P. J.; Waterson, C.; Haddleton, D. M. ***Chem. Commun.*** 1997**, 683.**

11.(a).Banno, K.; Narasaka, K.; Mukaiyama, T. *Chem. Lett*. **1973**,1011. (b). Banno, K.; Narasaka, K.; Mukaiyama, T. *J. Am. Chem. Soc*. **1974**, 96, 7503.

12. (a). Kobayashi, S.; Murakami, M.; Mukaiyama, T. *Chem. Lett.* 1985**,1535. (b). Sato, S.; Matsuda, I.; Izumi, Y. *Tetrahedron Lett.*** 1986**, 27, 5517. (c). Ohkouchi, M.; Masui, D.; Yamaguchi, M.; Yamagishi, T. *Nippon Kagaku Kaishi*,** 2002**, 2, 223. (d). Vougioukas, A.**
E.; Reetz, M. T. *Tetrahedron Lett.* 1987**, 7, 793. (e). Zhang, X-X.; Li, W-D. Z.; *Org. Lett*.**

2002, **4, 3485. (f). Naruse, Y.; Ukai, J.; Ikeda, N.; Yamamoto, H.** ***Chem. Lett.*** 1985, **1451.**

(g). Keith Hollis, T.; Odenkirk, W.; Robinson, N. P.; Whelan, J.; Bosnich, B. ***Tetrahedron,***

1993, **25, 5415. (h). Singer, R. A.; Carreira, E. M.** ***Tetrahedron Lett.*** 1994, **25, 4323. (i).**

Shen, Z. L.; Ji, S-J.; Loh, T-P. ***Tetrahedron Lett.*** 2005, **3, 507. (j). Weghe, P, V.; Collin, J.**

Tetrahedron Lett. 1993, **24, 3881. (k). Phukan, P.** ***Synth. Commun.*** 2004, **6, 1071. (l). Loh,**

T.P.; Ji, S-J.; Chen, S-L. ***Tetrahedron Lett.*** 2004, **45, 375. (m). Yamamoto, Y.; Maruyama,**

K.; Matsumoto, K.; ***Tetrahedron Lett.*** 1984, **10, 1075. (n). Creger, P. L. Tetrahedron Lett.**

1972, **1, 79. (o). Gorrichon, L.; Genisson, Y.** ***Tetrahedron Lett.*** 2000, **41, 4881. (p).**

Mikami, K.; Yamamka, M.; Islam, N.; Kudo, K.; Seino, N.; Shinoda, M. ***Tetrahedron Lett.***

2003, **44, 7545.**

13. Matsukawa, S.; Okano, N.; Imamoto, T. ***Tetrahedron Lett.*** 2000, **41, 103.**

14. Sogah, D. Y. ***US Patent,*** **4, 448, 980,** 1984.

15. Hertler, W. R.; Webster, O. W.; Cohen, G. M.; Sogah, D.Y. *Macromolecules* **1987**, 20, **1473**

16. Scheeren, H. W.; Aben, R. W. M.; Ooms, P. H. L.; Nivard, R. J. F. ***J. Org. Chem.*** 1977, **42,**

3128.

17. Satoh, K.; Kamigaito, M.; Sawamoto, M. ***Macromolecules,*** 1999, **12, 3827.**

18. Forsberg, J. H.; Spaziano, V. T.; Balasubramanian, G. K.; Liu, G. K.; Kinsley, S. A.; Duckworth, C. A.; Poteruca, J. J.; Brown, P. S.; Miller, J. L. *J. Org. Chem.* **1987**, *52*, 1017.

19. (a).Takahori, T.; Hachiya, I.; Kobayashi, S. ***Synthesis,*** 1993, **371. (b). Busujima, T.;**

Nagayama, S.; Kobayashi, S. ***J. Am. Chem. Soc.*** 1998, **120, 8287.**

20. Hong, Y.; Norris, D. J.; Collins, S. ***J. Org. Chem.*** 1993, **58, 3591.**

21. Reetz, M. T.; Raguse, B.; Marth, C. F.; Hugel, H. M.; Bach, T.; Fox, D. N. A. ***Tetrahedron,***

1992, **27, 5731.**

22. Brittain, W.J. ***Makromol. Chem. Macromol. Symp.*** 1993, **67, 373.**

23. Baskaran, D. ***Prog. Polym. Sci.*** 2003, **28, 521.**

Chapter 4: Synthesis and Characterization of Lactone-End Capped Poly (methyl methacrylate) s via Group Transfer Polymerization

4.1 Introduction

End functionalization of polymer chains confers useful properties to materials[1]. Functional polymers have been explored for a wide range of applications, such as, supported catalysis, biomedical applications, paints and varnishes as well lube and fuel additives[2]. End-functionalized polymers are also useful precursors for preparing block, graft, star-branched copolymers and network structures[3].

End-functional polymers can be prepared[4(a)] using techniques of living polymerization, such as

group transfer polymerization (GTP)[4(b)], living anionic polymerization (LAP)[4(c), (d)], and controlled radical polymerization (CRP) such as atom-transfer polymerization (ATRP)[4e], stable free radical polymerization (SFRP)[4f], and reversible addition fragmentation transfer (RAFT)[4g-h] which are expected to proceed in the absence of irreversible chain transfer and chain termination reactions. However, the nature of the polymer and the functional group to be introduced will determine the specific choice of synthetic methods as well as the reaction conditions needed to accomplish the functionalization successfully.

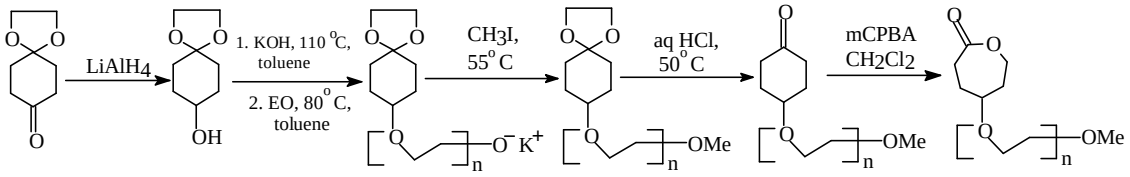
End functionalized poly (methyl methacrylate) s (PMMA) can be synthesized either by living anionic polymerization or controlled radical or group transfer polymerization. In general, two approaches are possible via, use of functional initiators or termination of the "living" chain by a
suitable electrophile (or radical precursors) bearing the functional groups. Either of the methods have both merits and demerits.

Use of functional initiators in GTP and anionic polymerization ensures that each polymer chain contains one functional group. However, initiators of this type are not easily accessible. Further more, such initiators generally require protection of the functional group since groups, such as, hydroxyl, amino, and carbonyl, are not compatible with the chain ends of living polymers. To overcome this problem, protection of reactive functional groups is resorted to anionic polymerization[5] and GTP[6-10]. Hydroxyl, carboxylic acid[7] and phenol end functional PMMA[8] has been prepared by GTP using appropriately protected initiators.

Use of electrophiles as terminating agents is not always efficient since in most cases, the active chain ends are in equilibrium with an inactive dormant species, which is incapable of reacting with the electrophile. Furthermore, need for low temperatures for controlled ionic polymerization or chain end aggregation, makes the reaction of the nucleophilic chain end with an electrophile less favorable. An additional complication arises due to competing termination reactions, leading to loss of active chain ends.

Relatively little attention has been paid to the study of GTP technique for the synthesis of end-functional poly (alkyl methacrylate) s by 'electrophilic termination' of the living ketene silyl acetal chain ends. Hydroxy[7], bromine[9], amine[10] end-functional and a styryl ended macromonomer[11] of poly (methyl methacrylate) is reported by terminating the living GTP chain-ends of PMMA with benzaldehyde, bromine, methyl E-3- (2-dimethylaminophenyl)-2-phenylacrylate and with 4-(bromomethyl) styrene respectively with varying efficiencies.

Recently Jerome reported[12] novel lactone end-capped poly (ethylene oxide) (PEO) as a new building block for biomaterials. PEO chains end-capped by an ε-caprolactone unit (γPEO.CL) with $M_{n,\,SEC}$ 800 and 1250 g/mol (M_w/M_n = 1.09-1.12) have been synthesized by living anionic ring-opening polymerization of ethylene oxide initiated by the potassium alkoxide of 1,4-dioxaspiro [4.5] decan-8-ol followed by derivatization of the acetal into a ketone and Baeyer-Villiger oxidation of the ketone (100% conversion) into a lactone (Scheme 4.1).



Scheme 4.1. Synthesis of macromonomer (γPEO.CL)

The end-capping of PEO by ε-CL was assessed by FTIR, MALDI-ToF MS, and ^{1}H NMR spectroscopy. This type of macromonomer is a precursor of amphiphilic comb like copolymers consisting of a biodegradable hydrophobic backbone of poly (ε-caprolactone) and hydrophilic PEO grafts. Copolymerization of γPEO.CL with ε-CL was successfully initiated by aluminum alkoxide. A bimodal molecular weight distribution is observed as a result of contamination of unreacted macromonomer (γPEO.CL) The yield of copolymer free of nonreacted γPEO.CL (with $M_{n,\,NMR}$ 39000 g/mol) after purification was 50%.

The Michael addition reaction, namely, the conjugate addition of O-silylated ketene acetals to α,β-unsaturated ketones (Mukaiyama-Michael reaction) is a well documented and important

method for carbon-carbon bond formation.[13] Rajan Babu reported[14] the first successful Mukaiyama-Michael reaction of trimethyl silyl ketene acetals with α,β-unsaturated ketones catalyzed by tris (dimethylamino) sulfonium difluorotrimethyl siliconate (TASF). Under these conditions silylated 1,4-adducts could be isolated.

As a part of our studies aimed at exploring the scope of eletrophilic termination approach of GTP chain ends for the synthesis of end functional PMMA's, we herein report the preparation of lactone-end capped PMMA using two approaches, namely, by the reaction of GTP chain ends with 2-cyclohexene-1-one followed by Baeyer-Villiger oxidation of the cyclohexanone end functionalized PMMA and, second, by the reaction of silyl ketene acetal chain ends of PMMA with 5, 6-dihydro-2H-pyran-2-one using tetra-n-butyl ammonium bibenzoate (TBABB) as catalyst. The efficiency of polymer functionalization was studied using ^{1}H NMR, SEC and MALDI-ToF MS methods. To the best of our knowledge this is the first reported attempt to synthesize lactone-end capped PMMA's.

4.2 Experimental Methods

4.2.1 Materials

2-Cyclopentene-1-one**,** 2-cyclohexene-1-one**,** methyl vinyl ketone, 3-methyl-2-cyclohexene-1-one, isophorone, mesityloxide, 2(5H)-furanone, and 5, 6-dihydro-2H-pyran-2-one all are procured from Aldrich, USA were distilled under reduced pressure and stored under nitrogen at 10^{o}C. $NaHCO_3$ (99%, Thomas Baker), m-CPBA (77% max., Aldrich, USA) and CF_3SO_3H (99%, Aldrich, USA) used as received.

4.2.2 Model reactions

Mukaiyama-Michael addition reaction of MTS to α,β-unsaturated ketones using tetra-n-butyl ammonium bibenzoate as a nucleophilic catalyst

A flame dried 50 mL round bottom flask was charged with 2.46×10^{-3} mmols of TBABB catalyst (0.1 mol% based on silyl ketene acetal **2**). Dry THF (10 mL) was transferred using a canula and stirred at room temperature. MTS **2** (1.1 equivalents) was added and stirred for 5 minutes. Subsequently 2.46 mmols of the desired α,β-unsaturated ketone was added in one lot under nitrogen gas and the reaction continued either at room temperature or under reflux

conditions. No attempt was made to isolate the silyl enol ether intermediates. Reaction mixture was quenched with 1N HCl and stirred at 0^{o}C for 0.5 h, water separated, product extracted into ethyl acetate and dried over Na_2SO_4.

After concentration of the organic layer, thin layer chromatography (60-120-mesh silica gel, EtOAc+ n-hexane as eluent) afforded δ-ketoester **3(a-d)** and **5(a-b)** (Scheme 4.2) in high yields (Table 4.1).

3a: light yellow liquid, FT-IR (neat); ν_{max} 1732, 1699 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$); δ 1.11 (s, 6H); 1.49-2.55 (m, 7H); 3.59 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$); δ 22.49, 24.29, 38.63, 40.28, 43.70, 44.95, 51.56, 177.02, 217.71; DEPT: -CH_2 (24.06, 38.47, 40.05); Anal. Calcd. for $C_{10}H_{16}O_3$ (184.23); C, 65.19; H, 8.75. Found: C, 65.76; H, 9.0.

3b: light yellow liquid, FT-IR (neat); ν_{max} 1734, 1716 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$);δ 1.19 (s, 6H); 1.40-2.95 (m, 9H); 3.60 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$); δ 20.83, 24.10, 25.35, 40.13, 42.26, 44.91, 50.72, 176.21, 209.80; DEPT: -CH_2 (24.65, 25.86, 40.67, 42.80); Anal. Calcd. for $C_{11}H_{18}O_3$ (198.26); C, 66.64; H, 9.15. Found C, 66.76; H, 9.27.

3c: light yellow liquid, FT-IR (neat) ν_{max} 1734, 1712 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$); δ 0.85 (s, 3H); 1.14 (s, 6H); 1.64 (m, 2H); 1.73 (m, 1H); 1.92 (m, 1H); 2.14 (d, *J* = 13.51 Hz, 1H); 2.17 (dd, *J* = 7.16, 13.12 Hz, 1H); 2.28 (m, 1H); 2.48 (d, J = 13.51 Hz, 1H); 3.60 (s, 3H); ^{13}CNMR (50 MHz, $CDCl_3$); δ 19.11, 20.80, 21.50, 30.83, 36.86, 40.57, 42.45, 48.81, 51.34, 176.69, 211.90; DEPT: -CH_2 (48.65, 40.45, 30.56, 21.34); Anal. Calcd for $C_{12}H_{20}O_3$ (212.287); C, 67.89; H, 9.49. Found C, 67.98; H, 9.60.

3d: light yellow liquid, FT-IR (neat) ν_{max} 1736, 1670 cm^{-1}; Anal. Calcd for $C_{14}H_{24}O_3$ (240.34); C, 69.96; H, 10.06. Found C, 70.0; H, 10.14.

5a: light yellow liquid, FT-IR (neat) ν_{max} 1738, 1726 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$); δ 1.07 (s, 6H); 1.69 (t, *J* = 8.06, 2H); 2.04 (s, 3H); 2.31 (t, *J* = 7.95, 2H); 3.56 (s, 3H); ^{13} CNMR

(200 MHz, $CDCl_3$); δ 24.84, 29.55, 33.70, 39.14, 41.31, 51.45, 177.50, 207.64; DEPT: - CH_2 (33.39, 38.91); Anal. Calcd for $C_9H_{16}O_3$ (172.22); C, 62.76; H, 9.36. Found C, 62.36; H, 9.34.

5b: light yellow liquid, FT-IR (neat) ν_{max} 1734, 1723 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$); δ 0.98 (s, 6H); 1.08 (s, 6H); 2.08 (s, 3H); 2.42 (s, 2H); 3.59 (s, 3H); ^{13}CNMR (50 MHz, $CDCl_3$); δ 21.02, 22.05, 32.85, 38.04, 48.88, 49.32, 51.34, 177.13, 208.92; DEPT: -CH_2 (48.98); Anal. Calcd for $C_{11}H_{20}O_3$ (200.27); C, 65.96; H, 10.06. Found C, 65.69; H, 9.97.

Baeyer-Villiger oxidation of cyclohexanone adduct (3b): To a mixture of cyclohexanone adduct (2 mmol) and $Yb(OTf)_3$ (10 mol%) or TfOH (20 mol%) in 20 mL of anhydrous CH_2Cl_2 at 0°C was added commercial grade *m*-CPBA (80% activity, 1.726 g, 8 mmol) and the mixture was stirred at room temperature while monitoring reaction with TLC. After completion of the reaction, the excess of the reagent was decomposed by addition of an aq. $Na_2S_2O_3$ solution. After concentration of the organic layer, thin layer chromatography (60-120-mesh silica gel, EtOAc+ n-hexane as eluent) afforded lactone adduct in high yields. FT-IR spectrum shows ester >C=O at 1728 cm^{-1}

Model reaction of MTS with 5, 6-dihydro-2H-pyran-2-one

A flame dried 50 mL round bottom flask was charged with 1.2 mg of TBABB catalyst ($2.46x10^{-3}$ mmol, 0.1 mol% based on MTS **2**). Dry THF (10 mL) was transferred at room temperature using a canula. MTS **2** (1.1 equivalent) was added and stirred for 5 minutes. Subsequently 0.2 mL of 5, 6-dihydro-2H-pyran-2-one (2.46 mmol) was added under nitrogen and the reaction continued at 30°C. In case of Lewis acid catalyst, 10-mol% of $Yb(OTf)_3$ or I_2 was taken in dichloromethane along with cyclic α,β-unsaturated ester.

No attempt was made to isolate the cyclic silyl ketene acetal intermediates. $Yb(OTf)_3$ was recovered by filtration. Iodine was removed after washing the homogeneous reaction mixture with saturated sodium thiosulphate. The desilylation reaction was carried out using 2.46 mmol of TBAF/MeOH for 1 h at room temperature. The product was extracted into ethyl acetate and washed well with water and dried over Na_2SO_4. The concentrated organic layer was subjected

to column chromatography (60-120-mesh silica gel, EtOAc / *n*-hexane as eluent) affording the lactone adduct (**11b**) in high yields.

FT-IR (neat): 11a ν_{max} 1728, 1778 cm^{-1};
Elemental Analysis: Anal. Calcd. for $C_9H_{14}O_4$ (186.20): C, 58.05; H, 7.57. Found: C, 58.10; H, 7.60.

FT- IR (neat): 11b ν_{max} 1734, 1730 cm^{-1};
Elemental Analysis: Anal. Calcd. for $C_{10}H_{16}O_4$ (200.23): C, 59.98; H, 8.05. Found C, 60.00; H, 8.10.

4.2.3 Polymerization

Cyclohexanone-end capped PMMA

A flame dried two-neck 250 mL flask, equipped with a nitrogen inlet, and a dropping funnel was charged with 1.2 mg of TBABB catalyst ($2.35x10^{-6}$ mol, 0.1mol% of MTS) in THF (1 mL), followed by dry THF (30 mL) was transferred using a canula under a positive pressure of dry nitrogen. 0.5 mL of MTS ($2.35x10^{-3}$ mol) was added using syringe at 30°C. After 5 minutes, 5.0 mL of MMA (0.047 mol) was added using a dropping funnel at approx. 1mL/min. Polymerization was continued for 30 minutes. An additional amount of TBABB catalyst (1.2 mg, $2.35x10^{-6}$ mol, 0.1 mol% MTS) in THF was added to the polymer solution. After 5 minutes, 0.25 mL of 2-Cyclohexene-1-one ($2.35x10^{-3}$ mol) was added. The reaction was allowed to continue for 12 h 30°C. Subsequently, $2.35x10^{-3}$ mol of NBu_4F/methanol was added to the reaction mixture and stirred at 30°C for 2 h. The polymer was isolated by precipitation from hexane. The polymer was further purified by reprecipitating it from THF solution using an excess of n-hexane. The obtained polymer was dried at 60°C in vacuum. Yield: 4.9 g (100 %).

SYNTHESIS OF LACTONE-END CAPPED PMMA VIA GTP

A flame dried two-neck 250 mL flask, equipped with a nitrogen inlet, and a dropping funnel was charged with 1.2 mg of TBABB catalyst ($2.35x10^{-6}$ mol, 0.1mol% of MTS) in THF (1 mL), followed by dry THF (30 mL) was transferred using a canula under a positive pressure of nitrogen. MTS (0.5 mL, $2.35x10^{-3}$ mol) was added using syringe at 30°C. After 5 minutes, 5.0 mL of MMA (0.047 mol) was added using a dropping funnel at approx. 1mL/min.

Polymerization was continued for 30 minutes. An additional amount of TBABB catalyst (1.2 mg, $2.35x10^{-6}$ mol, 0.1 mol% MTS) in THF was added to the polymer solution. After 5 minutes, 0.2 mL of 5,6-dihydro-2H-pyran-2-one ($2.35x10^{-3}$ mol) was added. The reaction was allowed to continue for 12 h 30^{o}C. Subsequently, $2.35x10^{-3}$ mol of NBu_4F/methanol was added to the reaction mixture and stirred at 30^{o}C for 2 h. The polymer was isolated by precipitation from hexane. The polymer was further purified by reprecipitating it from THF solution using an excess of n-hexane. The obtained polymer was dried at 60^{o}C in vacuum. Yield: 4.9 g (100 %).

4.2.4 Characterization

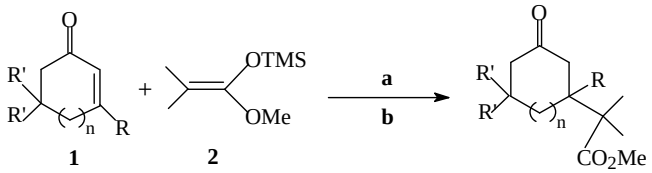
The methods of characterization have been described in chapter 2.

4.3 Results and Discussions

4.3.1 Reaction between MTS and α,β-unsaturated ketones

Use of TBABB as a mild catalyst for the Mukaiyama-Michael reaction of (1-Methoxy-2-methyl-1-propenoxy) trimethylsilane (MTS) **2** [$Me_2C=C(OMe)OSiMe_3$] with various α,β-unsaturated ketones was explored[15]. No reaction occurs in the absence of TBABB catalyst between the enones and MTS **2** in THF at room temperature. MTS **2,** which is a hindered ketene acetal, in the presence of bioxyanion (TBABB catalyst, 0.1 mol%) generates a very potent carbon nucleophile, equivalent to ester enolates. The addition to α,β-unsaturated ketone occurs efficiently in an exclusive 1,4 fashion giving δ-ketoesters in excellent yields (table 4.1).

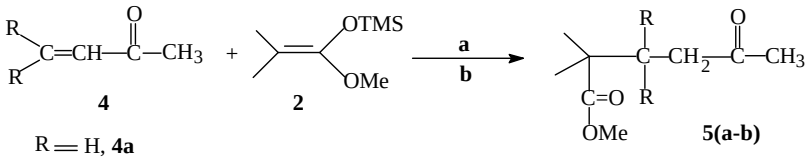
Scheme 1



1 2 3(a-d)

n = 0, R= H, R'= H, **1a**
n = 1, R= H, R'= H, **1b**
n = 1, R= CH_3, R'= H, **1c**
n = 1, R= CH_3, R'= CH_3, **1d**

Scheme 2



4 2 5(a-b)

R = H, **4a**
R = CH_3, **4b**

Reagents and Conditions: (a) Catalyst, TBABB (0.1 mol% of **2**), 10 mL THF. (b) THF: 1N HCl = 20:1, 0°C, 0.5 h

Scheme 4.2. Reaction between MTS and α,β-unsaturated ketones using TBABB catalyst

Simple Michael acceptors, such as, 2-cyclopentene-1-one (**1a),** 2-cyclohexene-1-one (**1b),** methyl vinyl ketone **(4a**) reacts with greater ease, even at room temperature (Scheme 4.2). Methyl vinyl ketone, the simplest α-enone which is an acid sensitive substrate, gave a Michael adduct (**5a)** in >95% yield without undergoing polymerization (entry 5 of table 4.1) using TBABB catalyst in THF. The reaction is exothermic and is completed in 10 minutes at 30°C. More hindered α,β-unsaturated ketones (3-methyl-2-cyclohexene-1-one (**1c)**, Isophorone (**1d)** and mesityloxide (**4b)**) require refluxing conditions for reaction to proceed to completion. Figure 4.1 and 4.2 shows ^{1}H and ^{13}C spectrum of cyclohexanone adduct (**3b**). Also, Figure 4.3 and 4.4 shows ^{1}H and ^{13}C NMR spectrum of isophorone adduct (**3d**, table 4.1) in $CDCl_3$.

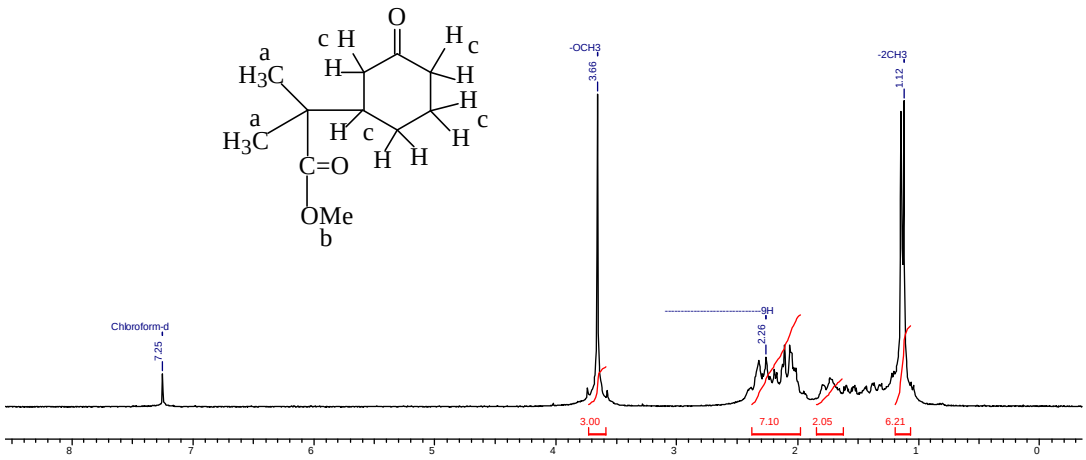


Fig 4.1. ^{1}H NMR spectrum of cyclohexanone adduct (**3b**, table 4.1) in $CDCl_3$ (200 MHz)

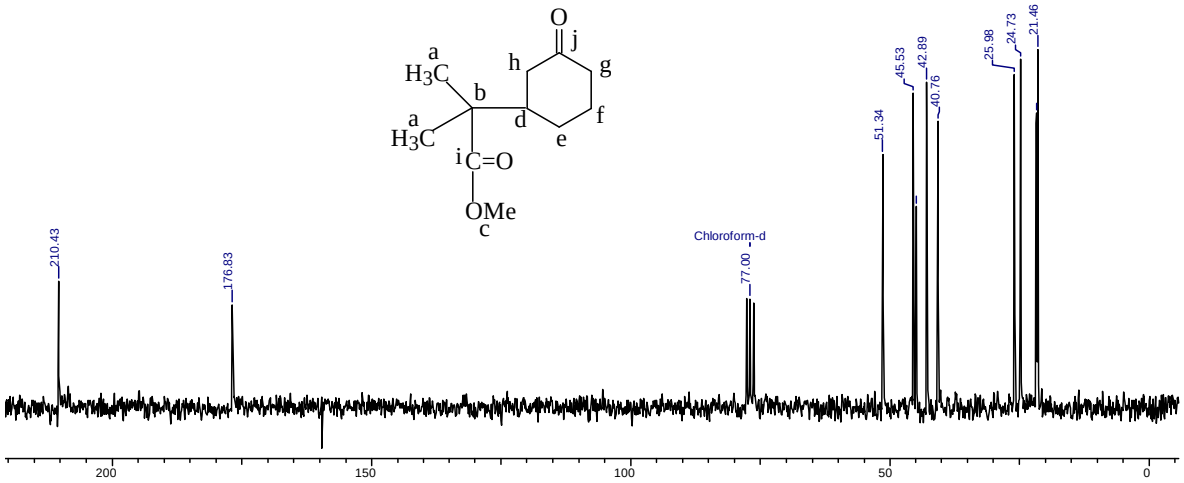


Fig 4.2. ^{13}C NMR spectrum of cyclohexanone adduct (**3b**, table 4.1) in $CDCl_3$ (50 MHz)

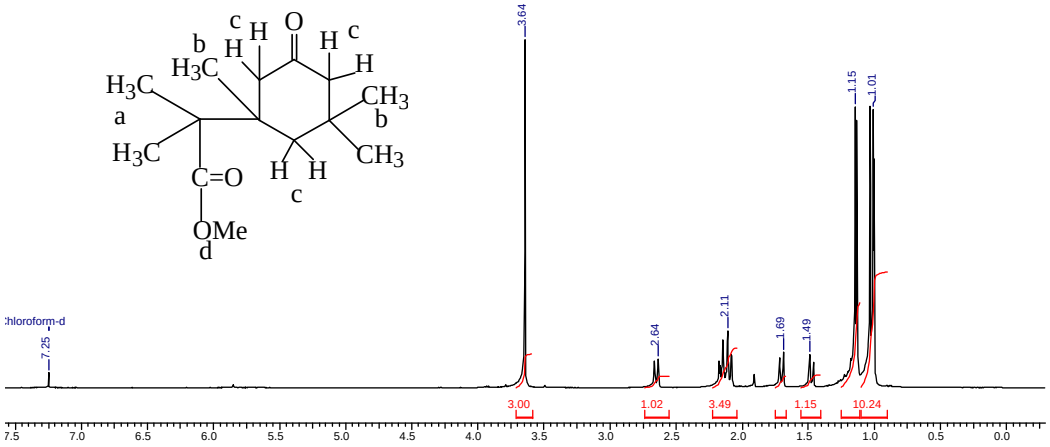


Fig 4.3. ^{1}H NMR spectrum of isophorone adduct (**3d**, table 4.1) in $CDCl_3$ (200 MHz)

Table 4.1 Reaction of α, β -unsaturated ketone[a] with MTS **2** using TBABB catalyst

Entry	α, β - unsaturated ketone	Reaction Temperature ^{o}C	Reaction time (minutes)	δ-Ketoester **3** or **5** Isolated Yield[b], %
1	Cyclopentene-1-one, **1a**	25	10	94 (**3a**)
2	2-Cyclohexene-1-one, **1b**	25	10	95 (**3b**)
3	3-Methyl, 2-Cyclohexene-1-one, **1c**	65	300	88 (**3c**)
4	Isophorone, **1d**	65	900	85 (**3d**)
5	Methyl vinyl ketone, **4a**	25	10	96 (**5a**)
6	Mesityloxide, **4b**	65	180	87 (**5b**)

[a] α,β-unsaturated ketone: 2.46 mmol, **2**: 2.46 mmol, TBABB: $2.46x10^{-3}$ mmol, THF: 10 mL.
[b] The purity of the δ-ketoester (≥98%) was checked by G.L.C and T.L.C

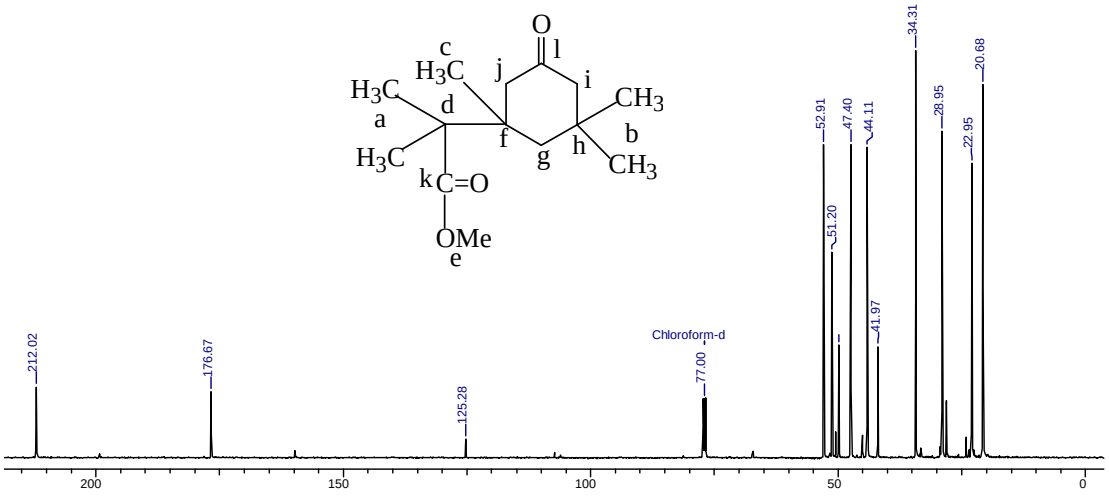


Fig 4.4. ^{13}C NMR spectrum of isophorone adduct (**3d**, table 4.1) in $CDCl_3$ (50 MHz)

Michael additions of α,β-unsaturated ketones (entry 1-6, table 4.2) resulted in high yields in the presence of catalytic amounts of $Yb(OTf)_3$ (10 mol%) as a reusable and water tolerant Lewis acid. Similar to nucleophilic TBABB catalyst, more hindered α,β-unsaturated ketones (3-methyl-2-cyclohexene-1-one (**1c)**, Isophorone (**1d)** and mesityloxide (**4b)**) require refluxing conditions for reaction to proceed to completion. These reactions are effectively carried out in dichloromethane. THF cannot be used since anhydrous $Yb(OTf)_3$ induces cationic ring-opening polymerization of THF[17].

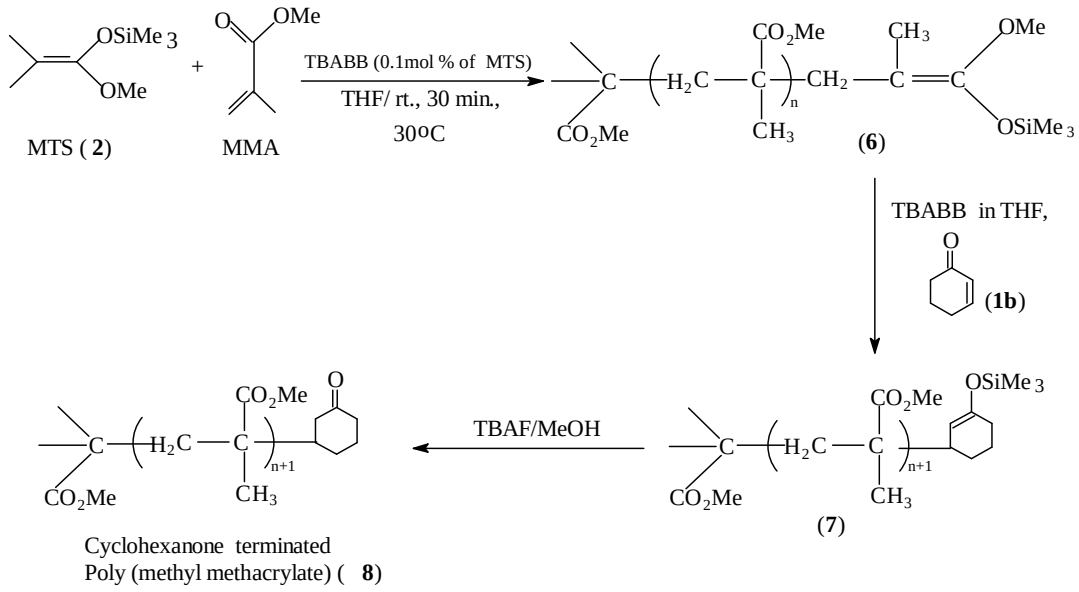
Table 4.2 Reaction of α, β - unsaturated ketone[a] with MTS **2** using 10-mol% $Yb(OTf)_3$ catalyst

Entry	α, β - unsaturated ketone	Reaction Temperature ^oC	Reaction time (minutes)	δ-Ketoester 3 or 5 Isolated Yield[b], %
1	Cyclopentene-1-one, **1a**	25	20	90 (3a)
2	2-Cyclohexene-1-one, **1b**	25	20	91 (3b)
3	3-Methyl, 2-Cyclohexene-1-one, **1c**	40	400	80 (3c)
4	Isophorone, **1d**	40	1000	75 (3d)
5	Methyl vinyl ketone, **4a**	25	20	89 (5a)
6	Mesityloxide, **4b**	40	240	80 (5b)

[a] α,β-unsaturated ketone: 2.46 mmol, **2**: 2.46 mmol, $Yb(OTf)_3$: 0.246 mmol, CH_2Cl_2: 10 mL.
[b] The purity of the δ-ketoester (≥98%) was checked by G.L.C and T.L.C

4.3.2 Cyclohexanone end-functionalized PMMA via group-transfer polymerization

The GTP of MMA was carried out using **MTS** (**2**) as initiator in THF at 30^{o}C using a TBABB (0.1 mol% of MTS). Living trimethylsilylketeneacetal-ended PMMA (**4**) was terminated with an electrophile, 2-cyclohexene-1-one, using 0.1-mol% TBABB catalyst (Scheme 4.3).



SCHEME 4.3. CYCLOHEXANONE-END FUNCTIONALIZED PMMA'S BY GTP

Cyclohexanone end functionalized PMMA (**5**) was obtained on desilylation using TBAF/ MeOH in quantitative yield. Figure 4.5 shows ^{1}H NMR spectrum of cyclohexanone-end capped PMMA (entry 1, table 4.3) in which protons of the cyclohexanone moiety appears in 1.0-1.70 range.

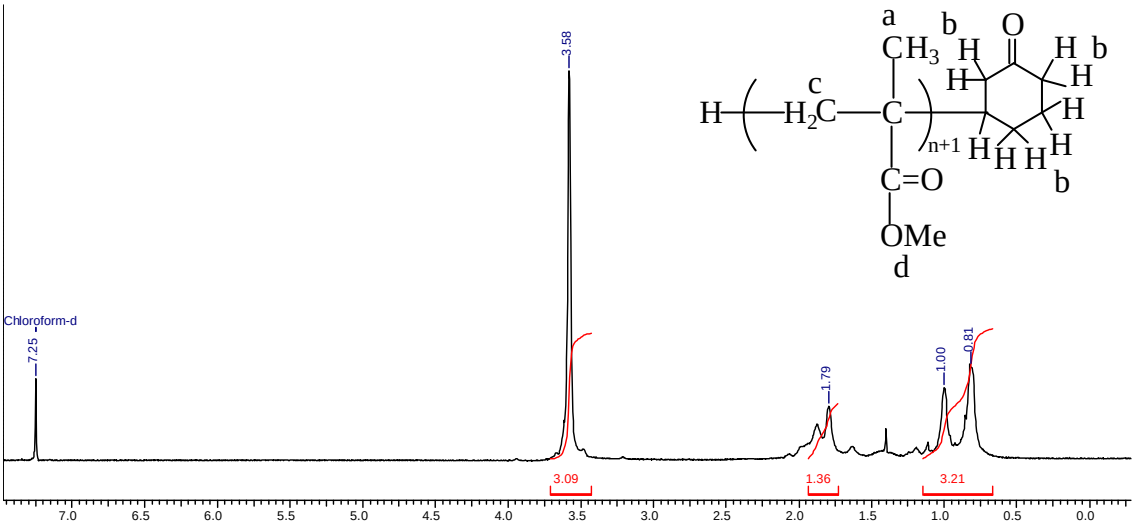
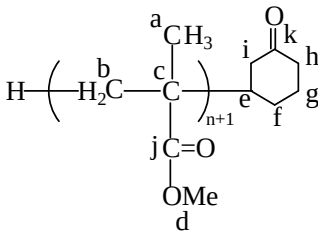


Fig 4.5. ^{1}H NMR spectrum of cyclohexanone-end capped PMMA (entry 1, table 4.3) in $CDCl_3$ (500 MHz)

Figure 4.6 shows ^{13}C NMR spectrum of cyclohexanone-end capped PMMA (entry 1, table 4.3) in which carbonyl carbon (C=O) due to ester of PMMA, cyclohexanone moiety end-group and cyclohexanone (of cyclized) comes at 177, 210 and at 176 ppm.



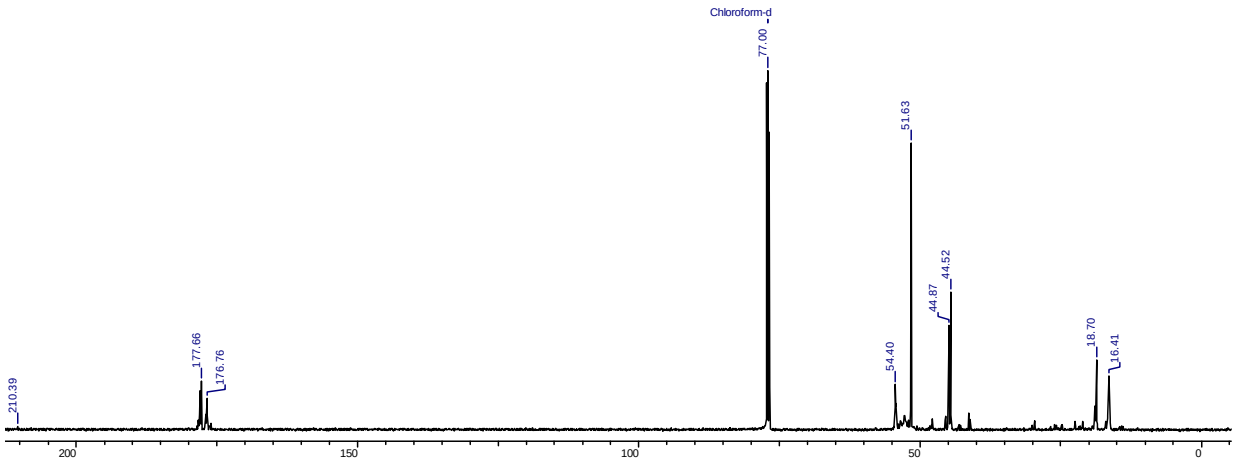


Fig 4.6. ^{13}C NMR spectrum of cyclohexanone-end capped PMMA (entry 1, table 4.3) in $CDCl_3$ (125 MHz)

Table 4.3. Characterization of cyclohexanone-end capped PMMA

Entry	MMA[a], moles	MTS, moles x 10^3	THF, mL	TBABB, moles x 10^6	2-Cyclohexene-1-one, moles x 10^3	M_n (theory), g/mol	M_n(SEC), g/mol	M_w/ M_n (SEC)	I^b efficiency
1	0.047	2.35	30	2.35	2.35	2097	2442	1.12	0.85
2	0.047	1.56	30	1.56	1.56	3097	2879	1.14	1.07

a: $[MMA]_0$ = 1.56 mol/L

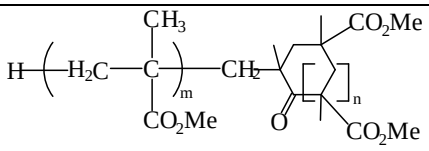
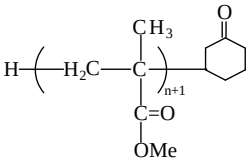
b: $I_{efficiency} = M_n$ (theory)/M_n (SEC)

MALDI ToF spectrum of cyclohexanone-end functionalized PMMA was performed by dissolving the polymer in THF (3 mg/mL) and mixed with the matrix 2,5-dihydroxybenzoic acid (10 mg/mL solution in THF) in a 1:1 proportion. For enhancement of ion formation, a small amount of LiCl was added to the solution. After depositing 0.5 µL of the solution on the sample holder the solvent was evaporated in hot air. MALDI -ToF spectrum of cyclohexanone-end capped PMMA is shown in Figure 4.7 in which the mass peaks correspond to the $[M+Li]^+$ molecular ions. $[M+Li]^+$ = 100.12 (MMA)* n(DP) + H(1.0079) + EG* (C_6H_9O) (97.1371) + 6.9(Li) for e.g. n= 20 gives M_n= 2107.486 g/mol i.e., expected series of major fraction will be 2107.486, 2207.606, …….. etc. MALDI ToF exhibited a major series as 2101.17, 2201.29, …….etc with Δ= 6 Da (table 4.4). Additionally, low intensity peaks attributed to an oligomer series with cyclic end groups $[M+Li]^+$ = 100.12 (MMA) * n (DP) + H (1.0079) - OCH_3 (31.0342) + 6.9(Li) for e.g. n= 20 gives M_n =1979.3147 g/mol i.e., expected series of lower fraction will be 1979.3147, 2079.4347, 2179.5547……were also observed at mass numbers 1872.70, 1972.92,……..etc. with Δ= 6 Da (Figure 4.7).

In conclusion, cyclohexanone-end functionalized PMMA could be prepared using 0.1-mol% TBABB catalyst in THF at 25°C using 2-cyclohexene-1-one as an electrophile with initiator efficiency (0.85-1.07) and with narrow molecular weight distribution (M_w/M_n =1.12-1.14). Number average degree of functionality (F_n) could not be determined since NMR could not be used for calculation of M_n. MALDI-ToF characterization of cyclohexanone-end functionalized

PMMA showed the expected end groups along with a small fraction of the cyclic end group obtained by chain end functionalization.

Table 4.4. Different observed series in MALDI-ToF- MS of cyclohexanone end-functional PMMA[@] prepared via GTP

Polymer	Ion	End group	Observed series*
	Li^+	Cyclohexanone end group with n =1 i.e. loss of $-OCH_3$ from linear fraction	1872.70, 1972.92,…etc. with Δ= 6 Da
	Li^+	97.1371 (C_6H_9O)-cyclohexanone end group	2101.17, 2201.29, …etc. with Δ= 6 Da.

@ Matrix is 2, 5-dihydroxybenzoic acid (F.W: 154.13) with Li^+ (6.941) (LiCl salt)

* $[M+Li]^+$ = 100.12 (MMA)* n(DP) + H(1.0079) + EG* (C_6H_9O) (97.1371) + 6.9(Li)

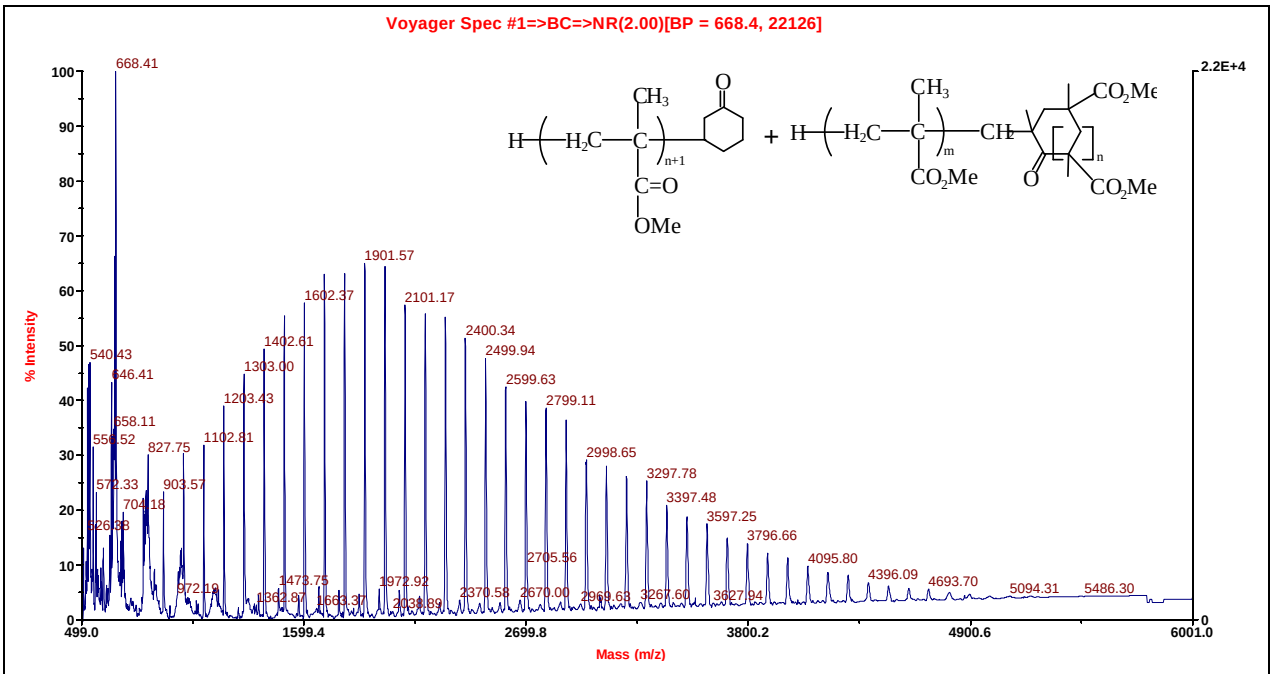
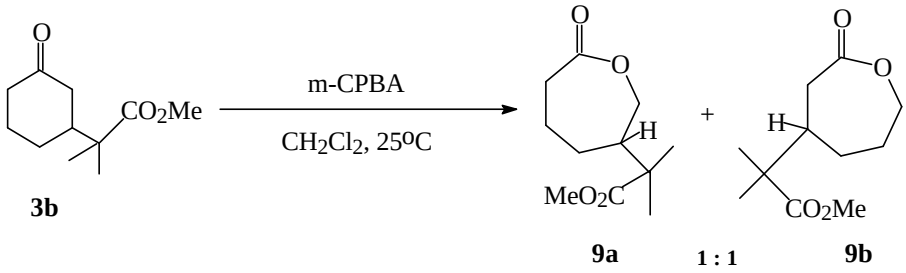


Fig 4.7. MALDI-ToF spectrum of cyclohexanone-end functionalized PMMA prepared by GTP using TBABB catalyst for silyl ketene acetal ended PMMA and TBABB for functionalization

reaction at room temperature (entry 1, table 4.3). $[M+Li]^+$ = 100.12 (MMA)* n(DP) + H(1.0079) + EG* (C_6H_9O) (97.1371) + 6.9(Li) (Matrix: Dihydroxybenzoic acid and LiCl for enhancement of ion formation) (Δ= 6 Da)

4.3.3 BAEYER-VILLIGER OXIDATION OF 3B

Baeyer-Villiger oxidation of **3b** was examined using m-chloroperbenzoic acid (m-CPBA) in presence of $Yb(OTf)_3$, trifluoromethane sulfonic acid (CF_3SO_3H) and $NaHCO_3$ as catalysts (Scheme 4.4). The results are shown in table 4.4. $Yb(OTf)_3$ and CF_3SO_3H were found to be very effective in promoting the reaction.



3b **9a** **1 : 1** **9b**

Scheme 4.4. Baeyer-Villiger oxidation of cyclohexanone adduct using m-CPBA

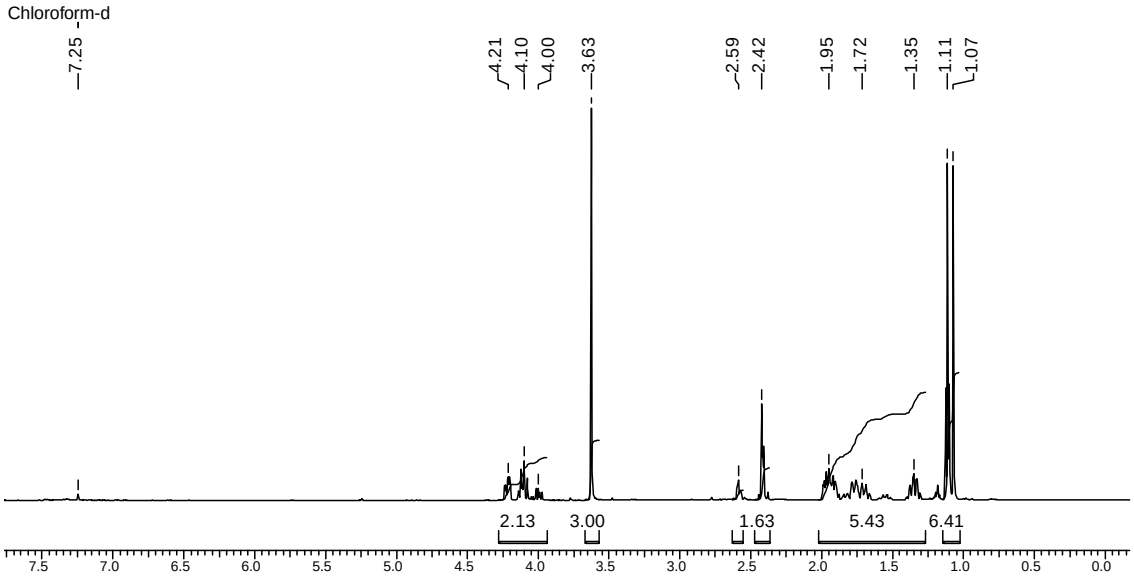
In the case of CF_3SO_3H (entry 4, table 4.5) anhydrous conditions were necessary to obtain good results.

Table 4.5. Baeyer-Villiger oxidation of 3b **using m-CPBA**

Entry	Cyclohexanone adduct, mmol	m-CPBA, mmol	Catalyst	Solvent, mL	Temp ^oC	Time h	**9a** + **9b**[a] %
1	2.0	8.0	None	CH_2Cl_2, 20	25	24	80
2	2.0	8.0	$Yb(OTf)_3$ 10 mol%	CH_2Cl_2, 20	25	10	83
3	2.0	8.0	$NaHCO_3$[b]	CH_2Cl_2, 20	25	20	72
4[c]	2.0	8.0	CF_3SO_3H 20 mol%	CH_2Cl_2, 20	25	4	90

a: isolated yields. b: 1.5 mol% excess of m-CPBA
c: water in m-CPBA was removed by drying over sodium sulphate

The structure of the reaction product was confirmed by ^{1}H and ^{13}C NMR (Figure 4.8 and 4.9).



The product was found to be a 1:1 mixture of isomers (**9a** + **9b**) by HPLC analysis.

Figure 4.8. ^{1}H NMR spectrum of lactone adduct (**9a** and **9b**) in $CDCl_3$ (500 MHz).

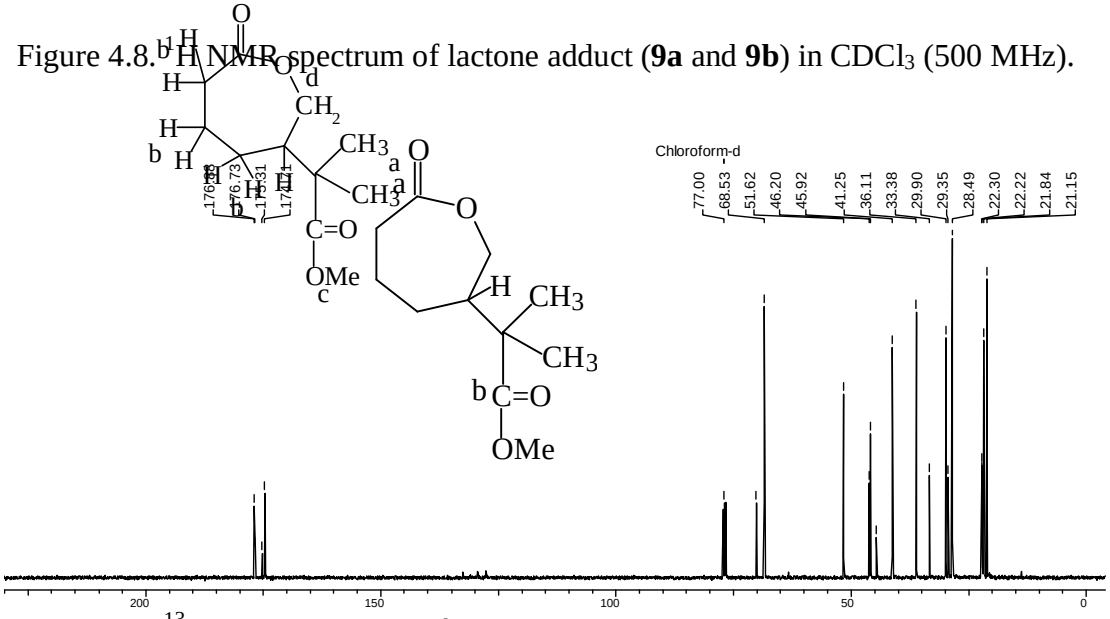


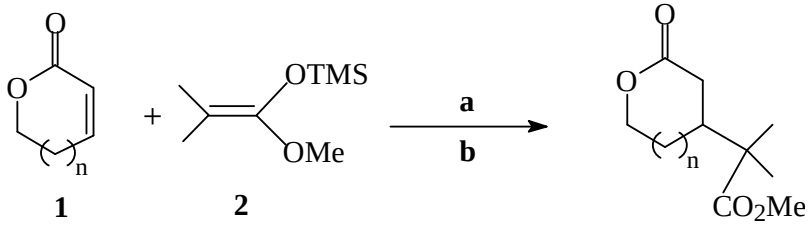
Figure 4.9. ^{13}C NMR spectrum of lactone adduct (**9a** and **9b**) in $CDCl_3$ (125 MHz)

Thus, Baeyer-Villiger oxidation of model compound **3b** using m-CPBA in conjunction with Lewis acids like $Yb(OTf)_3$ (10 mol%) or Bronsted acid like CF_3SO_3H (20 mol%) in dichloromethane gives the corresponding lactone in high yields.

However, the extension of these reaction conditions to the Baeyer-Villiger oxidation of the cyclohexanone end-functionalized PMMA (**8**, entry 1, table 4.3) failed to give any evidence of the formation for lactone end functionalized PMMA. Therefore, this approach to the preparation of lactone end functionalized PMMA was not further pursued.

4.3.4. Reaction between MTS 2 and α,β-unsaturated cyclic esters

Michael addition reaction of MTS to α,β-unsaturated lactones, namely, 2(5H)-furanone, and 5, 6-dihydro-2H-pyran-2-one can be efficiently carried out using TBABB as catalyst in THF as solvent[16]. The 1,4-adducts of 2(5H)-furanone (**10a**) and 5,6-dihydro-2H-pyran-2-one (**10b**) were obtained using either a Lewis acid ($(Yb(OTf)_3$ and I_2) catalyst or a nucleophilic catalyst (TBABB) with MTS **2** (Scheme 4.5). No reaction occurred between the cyclic α,β-unsaturated ester and MTS **2** in the absence of a catalyst in THF at room temperature. MTS **2**, which is a hindered ketene acetal in presence of the catalyst, generates a very potent carbon nucleophile, which in reactivity is equivalent to ester enolates.



1
n = 0, **10a**
n = 1, **10b**

2

11(a-b)

Reagents and conditions: (a) catalyst, solvent (b) TBAF/ MeOH, 30°C, 1 h

Scheme 4.5. Reaction between MTS and α,β-unsaturated cyclic esters

The addition to cyclic α,β-unsaturated esters was clean and occurs efficiently in an exclusive

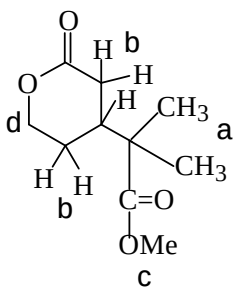
1,4-fashion without any complication from 1,2-addition or undesired condensation reaction etc. The representative results are summarized in table 4.6. Compared to Lewis acids, TBABB is easy to prepare from readily available starting materials, is crystalline, non-hygroscopic, soluble in THF and can be stored and handled with much greater ease.

Table 4.6. Reaction of α,β-unsaturated lactones[a] with MTS **2**

Entry	α,β-unsaturated lactones	Catalyst, (mol%)	Solvent, (mL)	Catalysis	Reaction time (h)	Isolated yield (%)
1	5,6-Dihydro-2*H*-pyran-2-one	No catalyst	THF, 10	-	12	nil
2	2(5*H*)-Furanone	TBABB, 0.1	THF, 10	Homogeneous	1	92 **(11a)**
3	2(5*H*)-Furanone	$Yb(OTf)_3$, 10	CH_2Cl_2, 10	Heterogeneous	1	90 **(11a)**
4	5,6-Dihydro-2*H*-pyran-2-one	TBABB, 0.1	THF, 10	Homogeneous	1	94 **(11b)**
5	5,6-Dihydro-2*H*-pyran-2-one	$Yb(OTf)_3$, 10	CH_2Cl_2, 10	Heterogeneous	1	90 **(11b)**
6	2(5*H*)-Furanone	I_2, 10	CH_2Cl_2, 10	Homogeneous	4	90 **(11a)**
7	5,6-Dihydro-2*H*-pyran-2-one	I_2, 10	CH_2Cl_2, 10	Homogeneous	4	92 **(11b)**

[a] α,β-unsaturated lactone: 2.46 mmol, **2**: 2.46 mmol, Solvent: 10 mL. Reaction temperature: 25°C
[b] The purity of the adduct 3(a-b) (≥97%) was checked by G.L.C and T.L.C

Fig 4.10 shows ^1H NMR spectrum of lactone adduct in $CDCl_3$ in which the diastereotopic CH_3's could not be distinguished.



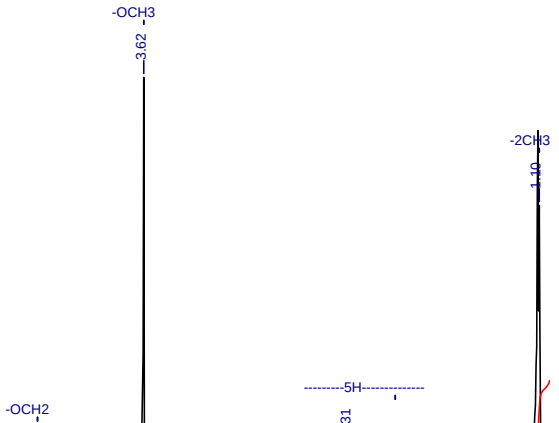


Fig 4.10. ^{1}H NMR spectrum of lactone adduct (**11b**) (entry 4, table 4.6) in $CDCl_3$ (200 MHz)

Fig 4.11 shows ^{13}C NMR spectrum of lactone adduct in $CDCl_3$ in which the diastereotopic methyl's could not be distinguished.

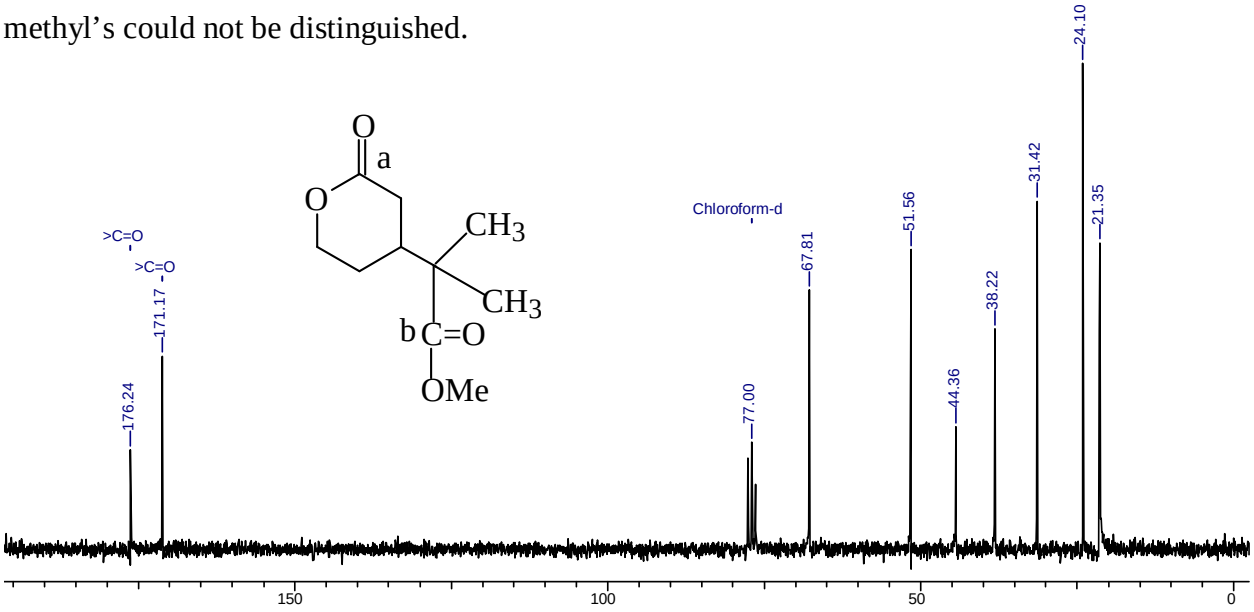


Fig 4.11. ^{13}C NMR spectrum of lactone adduct (**11b**) (entry 4, table 4.6) in $CDCl_3$ (50 MHz)

Fig 4.12 shows ^{1}H NMR spectrum of lactone adduct (entry 2, table 4.5) in $CDCl_3$ and Fig 4.13

shows ^{13}C NMR spectrum of lactone adduct in $CDCl_3$.

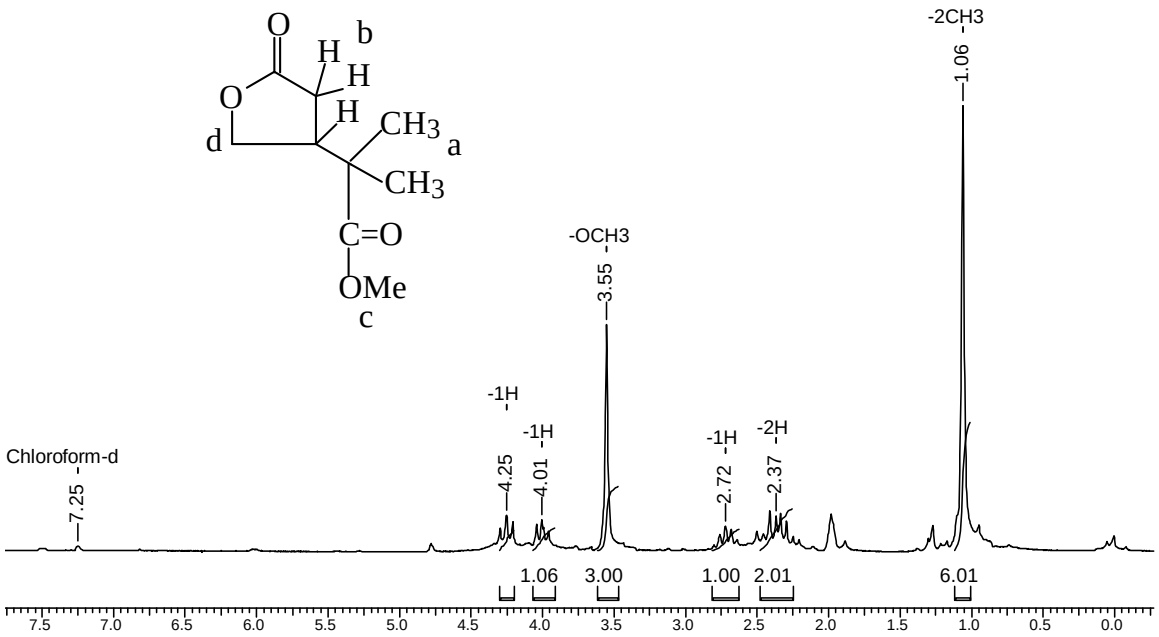


Fig 4.12. ^{1}H NMR spectrum of lactone adduct (**11a**) (entry 2, table 4.6) in $CDCl_3$ (200 MHz)

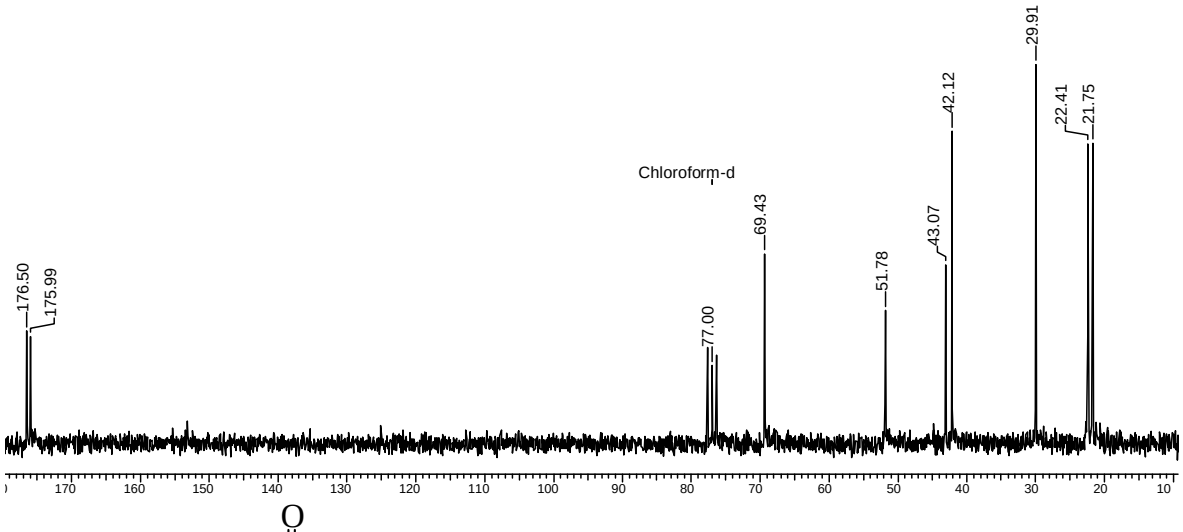
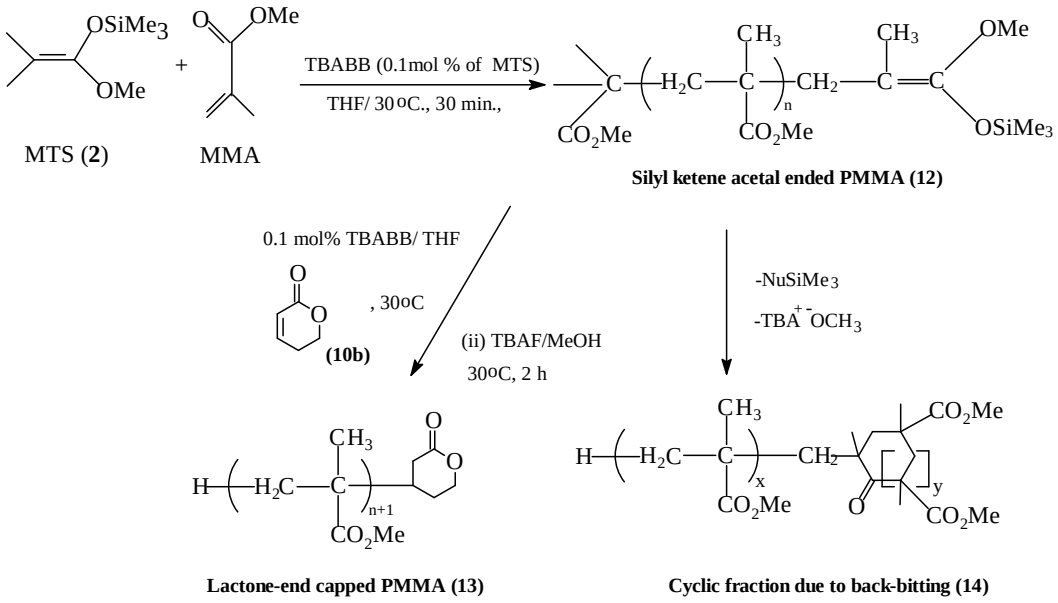


Fig 4.13. ^{13}C NMR spectrum of lactone adduct (**11a**) (entry 2, table 4.6) in $CDCl_3$ (50 MHz)

4.3.5. End functionalization reaction of GTP chain ends with 5, 6-dihydro-2H-pyran-2-one (1b)

The GTP of MMA was carried out using **MTS** (**2**) as initiator in THF at room temperature using a nucleophilic oxyanion catalyst, namely, TBABB (0.1 mol% of MTS). Living trimethylsilylketeneacetal-ended PMMA (**4**) was terminated with an electrophile 5, 6-dihydro-2H-pyran-2-one (**1b**) using 0.1 mol% TBABB catalyst (Scheme 4.6).



Scheme 4.6. Synthesis of lactone-end capped PMMA's via GTP

Lactone-end capped PMMA (**5**) was obtained on desilylation using TBAF/ MeOH in quantitative yield. Figure 4.14 shows ^{1}H NMR spectrum of lactone-end capped PMMA (entry 1, table 4.7). Functionalization efficiency of end-functional polymers was measured by calculating the area of peak corresponding to $-OCH_3$ of PMMA and $-OCH_2$ derived from the lactone protons (table 4.7). Fig 4.15 shows ^{13}C NMR spectrum of lactone-end capped PMMA (entry 1, table 4.7) in which there are three C=O peaks between 176 ppm and 178 ppm due to ester carbonyl of PMMA, cyclohexanone C=O (due to back bitting) and lactone C=O (lactone end group).

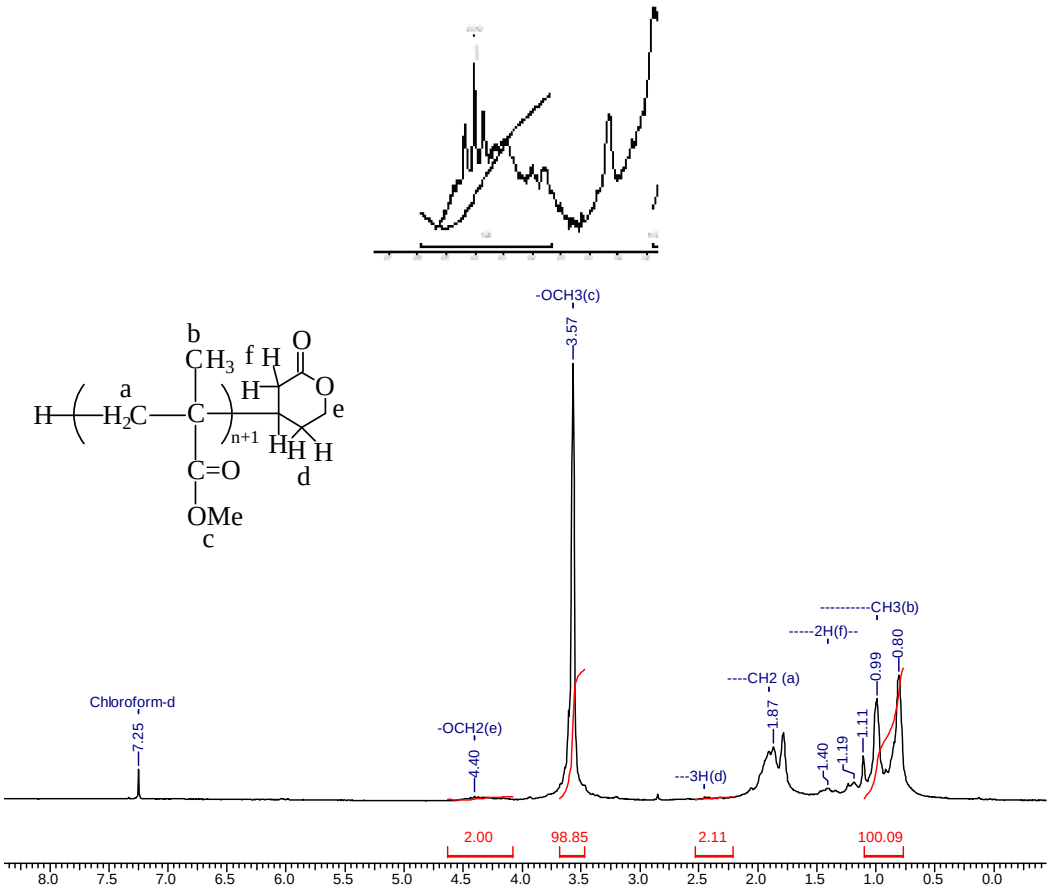


Fig 4.14. ^{1}H NMR spectrum of lactone-end capped PMMA (entry 1, table 4.7) in $CDCl_3$

Table 4.7. Characterization of lactone-end functionalized PMMA

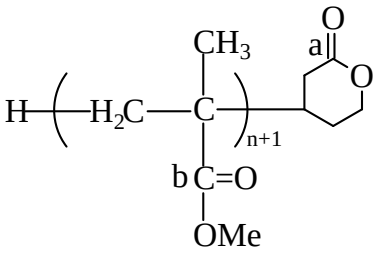
Entry	MMA[a], mol	MTS, mol x 10^3	THF, mL	TBABB, mol x 10^6	TBABB, mol x 10^6	5,6-Dihydro-2*H*-pyran-2-one, mol x 10^3	M_n (theory), g/mol	M_n (VPO), g/mol	M_n (SEC), g/mol	M_w/M_n (SEC)	M_n (NMR) g/mol	$I^b_{efficiency}$	F^c_n
1	0.047	2.35	30	2.35	2.35	2.35	2100	2400	2550	1.11	3300	0.83	0.77
2	0.047	2.35	30	2.35	2.35	2.35	2100	2700	2550	1.11	3200	0.82	0.80
3	0.047	1.56	30	1.56	1.56	1.56	3100	2800	2900	1.10	3560	1.05	0.82
4	0.047	2.35	30	2.35	2.35	2.35	2100	2400	2200	1.10	2800	0.96	0.78
5	0.047	2.35	30	2.35	2.35	2.35	2100	2700	2350	1.08	3200	0.89	0.73
6[d]	0.047	2.35	30	2.35	2.35	2.35	2100	2500	2600	1.20	3464	0.80	0.75

a: $[MMA]_0 = 1.56$ mol/L

b: $I_{efficiency} = M_n$ (theory)/M_n (SEC)

c: $F_n = M_n$ (SEC)/ M_n (NMR)

d: reaction was conducted at reflux temperature of THF



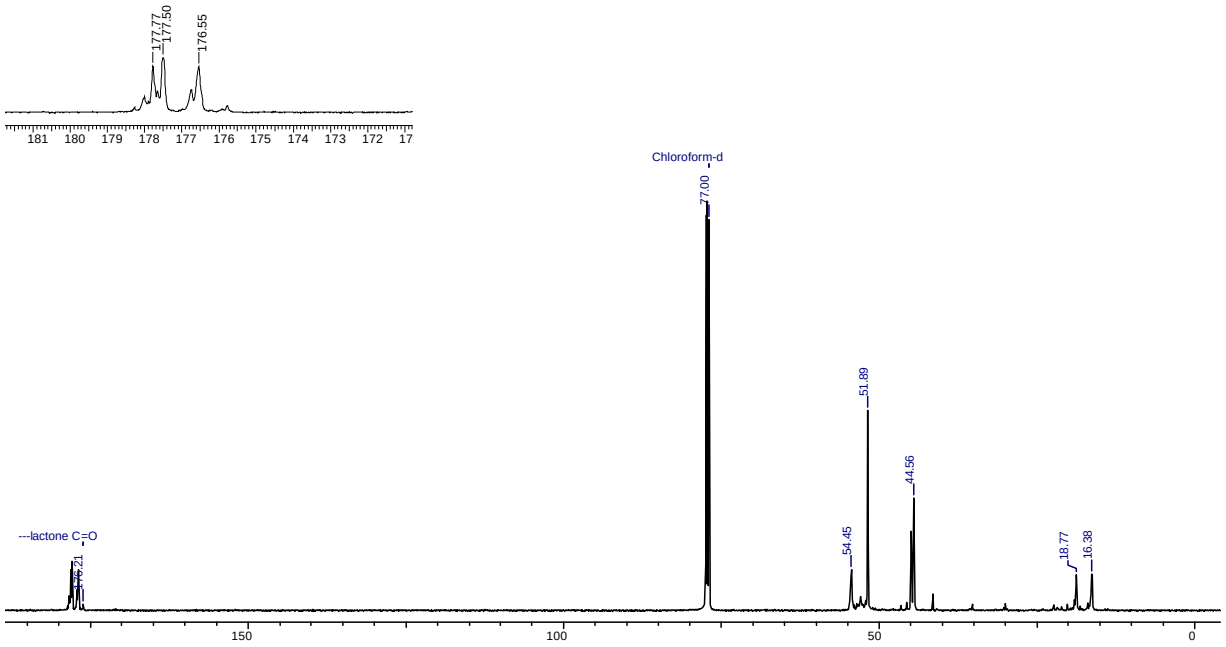


Fig 4.15. ^{13}C NMR spectrum of lactone-end capped PMMA (entry 1, table 4.7) in $CDCl_3$

MALDI ToF MS spectrum of lactone-end functionalized PMMA was performed by dissolving the polymer in THF (3 mg/mL) and mixed with the matrix 2,5-dihydroxybenzoic acid (10 mg/mL solution in THF) in a 1:1 proportion. For enhancement of ion formation, a small amount of LiCl was added to the solution. After depositing 0.5 µL of the solution on the sample holder the solvent was evaporated in hot air. A typical MALDI-ToF spectrum of lactone-end capped PMMA is shown in figure 4.16 (also figure 4.17), (entry 1, table 4.7). The expected mass peaks corresponds to the $[M+Li]^+$ = 100.12 (MMA)* n(DP) + H(1.0079) + EG* ($C_5H_7O_2$) (99.1096) + 6.9(Li) for e.g. n = 20 gives M_n= 2109.4585 g/mol i.e., expected series of major fraction will be 2109.4585, 2209.5785,…….. etc. MALDI ToF exhibited a major series (figure 4.16) as 2103.75, 2203.60, …….etc with Δ= 6 Da. Additionally, low intensity peaks attributed to an oligomer series with cyclic end groups $[M+Li]^+$ = 100.12 (MMA) * n (DP) + H (1.0079) - OCH_3 (31.0342) + 6.9(Li) for e.g. n= 20 gives M_n =1979.3147 g/mol i.e., expected series of lower fraction will be 1979.3147, 2079.4347, 2179.5547……were also observed at mass numbers 1873.70, 1973.82,……..etc. with Δ= 6 Da.

As strong evidence is now present for a dissociative anionic process for GTP[17], the second smaller homologous series (with mass difference between both homologous series is about 31 g/mol due to loss of –OCH_3 group as a result of backbiting reaction) must be attributed to the formation of cyclic structures (**14**, scheme 4.6) in addition to linear fractions. As the mass increment of both homologous series is the same (i.e. about 100 g/mol of MMA), the change in the chemical structure must be attributed to variations in the end-group.

The fact that both homologous series have their maximum abundance at about 2000 g/mol indicates that they are formed simultaneously in the reaction. This is in accordance with the observation that the living nature of GTP depends on the nature and concentration of catalyst[17] and also on molar mass of the polymer. Here we used 0.1 mol% of less nucleophilic TBABB catalyst to keep the cyclic fraction as low as possible. Different observed series in MALDI-ToF- MS of lactone end-functional PMMA prepared by GTP is shown in table 4.8.

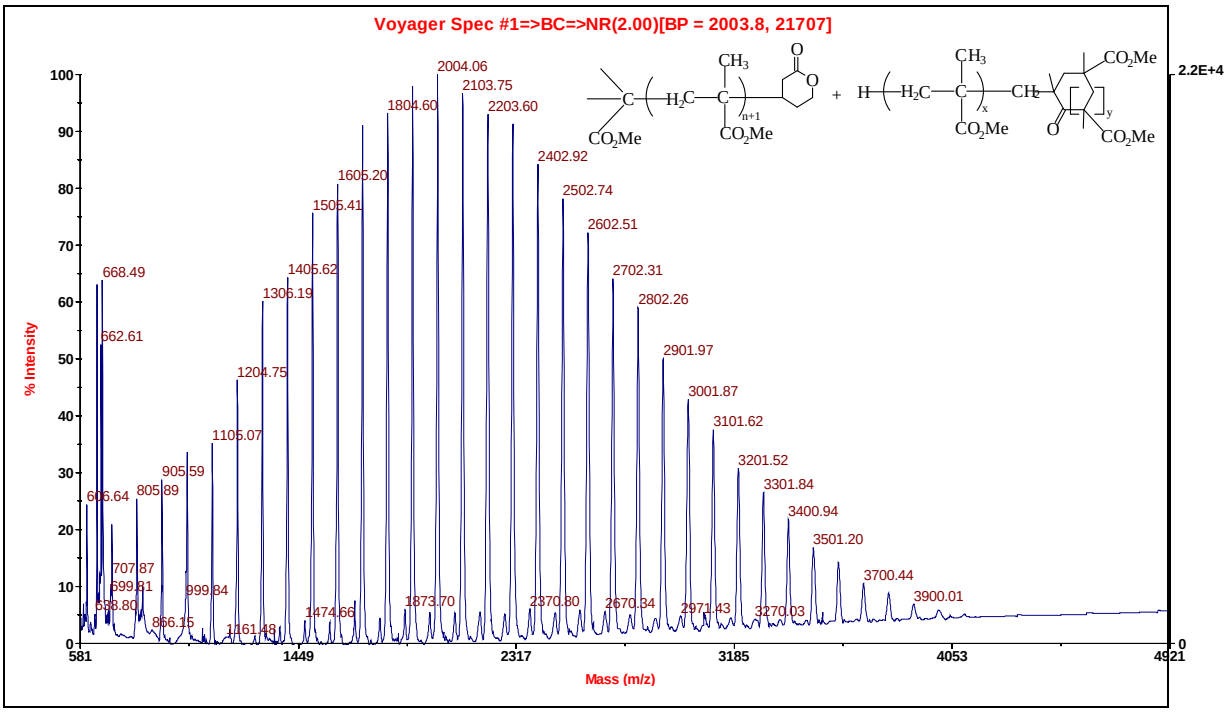
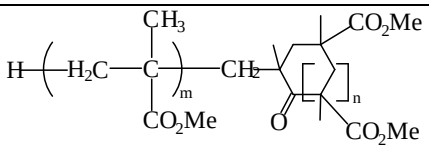
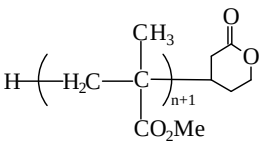


Fig 4.16. MALDI-ToF spectrum of lactone-end capped PMMA prepared by GTP using 0.1-mol% TBABB catalyst at 30°C (entry 1, table 4.7). $[M+Li]^+$ = 100.12 (MMA)* n(DP) + H(1.0079) + EG* ($C_5H_7O_2$) (99.1096) + 6.9(Li) (Matrix: Dihydroxybenzoic acid and LiCl for enhancement of ion formation) (Δ= 6 Da)

Table 4.8. Different observed series in MALDI-ToF- MS of lactone end-functional PMMA[a] prepared via GTP

Polymer	Ion	End group	Observed series[b]
	Li^+	Cyclohexanone end group with n =1 i.e. loss of $-OCH_3$ from linear fraction	1873.70, 973.82,…etc. with Δ= 6 Da
	Li^+	99.1096 ($C_5H_7O_2$)-Lactone end group	2103.75, 2203.60, …etc. with Δ= 6 Da.

a: Matrix is 2, 5-dihydroxybenzoic acid (F.W: 154.13) with Li^+ (6.941) (LiCl salt)

b: $[M+Li]^+$ = 100.12 (MMA)* n(DP) + H(1.0079) + EG* ($C_5H_7O_2$) (99.1096) + 6.9(Li)

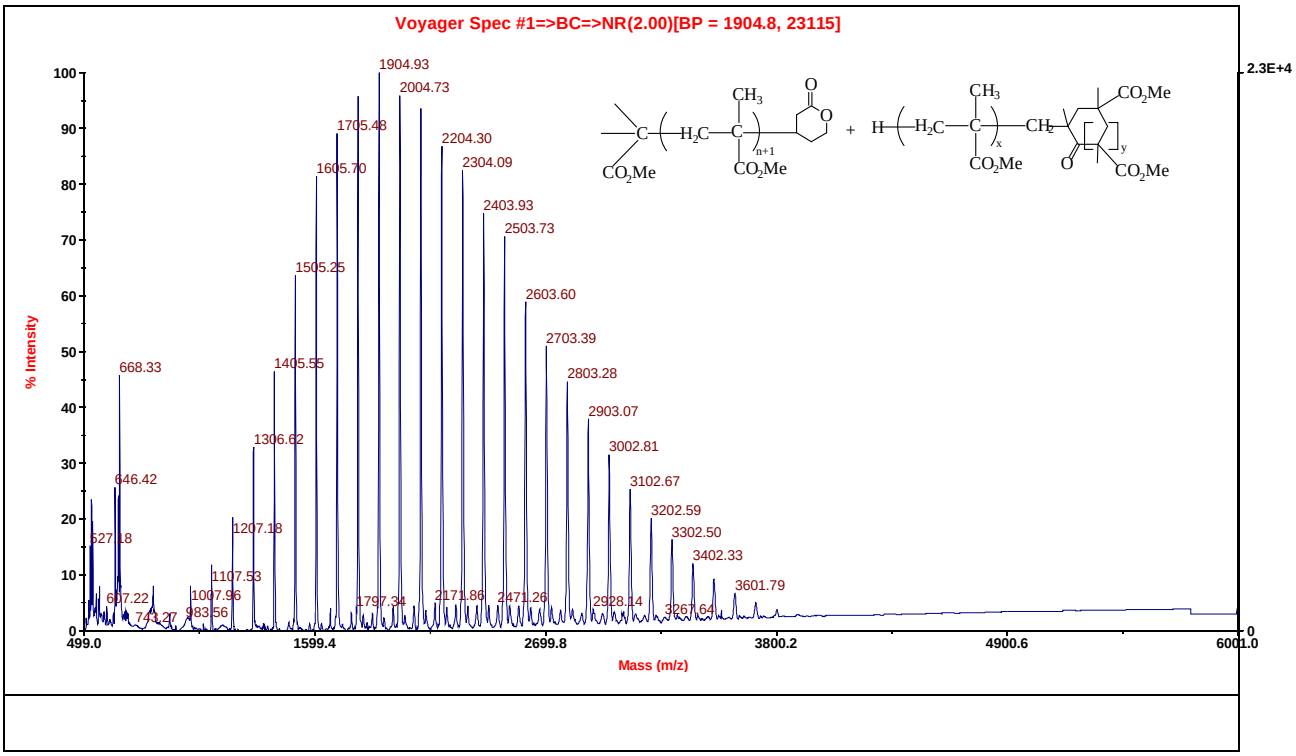


Fig 4.17. MALDI-ToF spectrum of lactone-end capped PMMA prepared by GTP using TBABB catalyst for silyl ketene acetal ended PMMA and TBABB for functionalization reaction at room temperature (entry 2, table 4.7). $[M+Li]^+$ = 100.12 (MMA)* n(DP)+ H(1.0079)+EG*($C_5H_7O_2$) (99.1096)+6.9(Li) (Matrix: Dihydroxybenzoic acid and LiCl for enhancement of ion formation) (Δ= 6 Da).

4.4 Conclusions

Lactone-end functionalized PMMA was prepared via GTP using 0.1-mol% TBABB as a catalyst in THF at 30^{o}C with satisfactory initiator efficiency (0.82-1.05) and narrow molecular weight distributions (M_w/M_n = 1.08-1.11). The number average degree of functionalization as determined by NMR/SEC was in the range of 0.70-0.85. MALDI-ToF-MS analysis of lactone-end functionalized PMMA provide evidence for competing chain end cyclization.

4.5 References

1. Arshady, R. Desk *Reference of Functional Polymers: Synthesis and Applications* ACS: Washington DC, **1997**.

2. (a). Sheats, C. E.; Pittman, C. U.; Zeldin, M.; Currell, B. *Inorganic and Metal Containing*

Polymeric Materials*; Plenum: New York** 1990**. (b). Patil, A.O. *Bulletin of Electrochemistry

1992**, 8, 509 and references therein.**

3. Quirk, R. P.; Ma, J. J.; Lizarraga, G.; Ge, Q.; Hasegawa, H.; Kim, Y. J.; Jang, S. H.; Lee, Y.

Macrmol. Symp. 2000**, 161, 37.**

4. (a). Patil, A. O.; Schulz, D. N.; Novak, M. in *Functional polymers: Modern synthetic methods and novel structures*; *ACS Symposium Series*, **1998,** 704. (b). Webster, O. W.; Sogah, D. Y. in *Recent advances in mechanistic and Synthetic aspects of polymerization*, **1987**, 3. (c). Mahua, G. Ph.D. thesis, **2002**, Pune University, India. (d). Hirao, A.; Hayashi, M.; Loykulnant, S.; Sugiyama, K.; Ryu, S. W.; Haraguchi, N.; Matsuo, A.; Higashihara, T. *Prog. Polym. Sci*. **2005**, 30, 111. (e). Matyjaszewski, K.; Xia, J. *Chem. Rev*. **2001**, 101, 2921. (f). Hawker, C. J.; Bosman, A.W.; Harth, E. *Chem. Rev* **2001**, 101, 3661. (g). Chiefari, J.; Chong, Y. K. B, Ercole, F.; Krstina, J.; Jeffery, J.; Letp, T.; Mayadunne, R. T. A.; Meijs, G. F.; Moad, C. L.; Moad, G.; Rizzardo, E.; Thang, S. H. *Macromolecules* **1998**, 31, 5559. (h). Mayadunne, R.T. A.; Rizzardo, E.; Chiefari, J.; Chong, Y. K.; Moad, G.; Thang, S. H *Macromolecules* **1999**, 32, 6977.

5. (a). Nakahama, S.; Hirao, A. *Progr. Polym. Sci.* 1990**, 15, 299. (b). Nakahama, S.; Hirao, A.**

Trends Polym. Sci. 1994**, 2, 283. (c). Dasgupta, A.; Sivaram, S. *J. Macromol. Sci. Rev. Macromol. Chem. Phys.*** 1997**, C (37) 1, 1.**

6. Webster, O. W.; Hertler, W. R, Sogah, D. Y.; Farnham, W. B.; RajanBabu, T. V. *J. Am.*

Chem. Soc. 1983**, 105, 5706**

7. Sogah, D. Y.; Hertler, W. R.; Webster, O. W.; Cohen, G. M. *Macromolecules* **1987**, 20, 1473

8. Webster, O. W.; Heitz, T. *Makromol. Chem.* **1991**, 192, 2463.

9. (a) Sogah, D. Y.; Webster, O. W. *J. Polym. Soc. Lett. Ed.* **1983**, 21, 927. (b) Eastmond, G. C.; Grigor, J. *Makromol. Chem., Rapid Commun*, **1986**, 7, 375.

10. Quirk, R. P.; Ren, J. *Polymer International* **1993**, 32, 205.

11. (a) Asami, R.; Kondo, Y.; and Takaki, M. *ACS Polymer Preprints* **1986**, 27, 186. (b)

Spinelli, H. J. *Adv. Org. Coat. Sci. Technol. Ser* **1990**, 12, 34. (c) Cohen, G. M. *ACS Polymer Preprints* **1988**, 29, 46.

12. Rieger, J.; Bernaerts, K. V.; Du Prez, F. E.; Jérôme, R.; Jérôme, C. *Macromolecules,* 2004**,**

37, 9738.

13. (a) Narasaka, K.; Soai, K.; Mukaiyama, T. *Chem. Lett.* **1974**, 1223-1226 (b) Narasaka, K.; Soai, K.; Mukaiyama, T. *Bull. Soc. Chem. Jpn.* **1976**, 49, 779-783 (c) Saigo, K.; Osaki, M.; Mukaiyama, T. *Chem. Lett.* **1976**, 163-164

14. Rajan Babu, T. V. *J. Org. Chem.* **1984**, *49*, 2083-2089 and references cited therein.

15. Gnaneshwar, R.; Wadgaonkar, P. P.; Sivaram, S. *Tetrahedron Lett*. **2003**, *44*, 6047-6049 and references cited therein.

16. Gnaneshwar, R.; Sivaram. S. *Synthetic Communications* **2006**, 36, 885.

17. (a). Webster, O. W. *Adv. Polym. Sci.* 2004**,167, 1. (b). Baskaran, D. *Prog. Polym. Sci.*** 2003**,**

28, 521.

Chapter 5: Synthesis and Characterization of Amine-Terminated Poly (methyl methacrylate) s via Group Transfer Polymerization

5.1 Introduction

Controlled synthesis of polymers with reactive functionality at the terminal end continues to be a synthetic challenge in polymer chemistry. End functional polymers are useful in a variety of applications, such as, compatibilizing agent for polymers via reactive processing, macromolecular surfactants, modification of surfaces etc. Several techniques of controlled polymerizations, namely, living anionic polymerization (LAP)[1], group transfer polymerization (GTP)[2] and controlled radical polymerization (CRP) such as atom-transfer polymerization (ATRP)[3a], stable free radical polymerization (SFRP)[3b], and reversible addition fragmentation transfer (RAFT)[3c-d] can be used for the synthesis of end-functionalized polymers. However, the nature of the polymer and the functional group to be introduced will determine the specific choice of synthetic methods.

End functionalized poly (methyl methacrylate) s can be synthesized either by living anionic polymerization or controlled radical or group transfer polymerization. In general, two approaches are possible via, use of functional initiators or termination of the “living” chain by a suitable electrophile (or radical precursors) bearing the functional groups. Either of the methods have both merits and demerits. For example, functional initiators having active hydrogen groups (-OH, -NH_2) cannot be directly used in LAP and will require a protection-deprotection sequence.

Use of electrophiles as terminating agents is not always efficient since in most cases, the active chain ends are in equilibrium with an inactive dormant species, which is incapable of

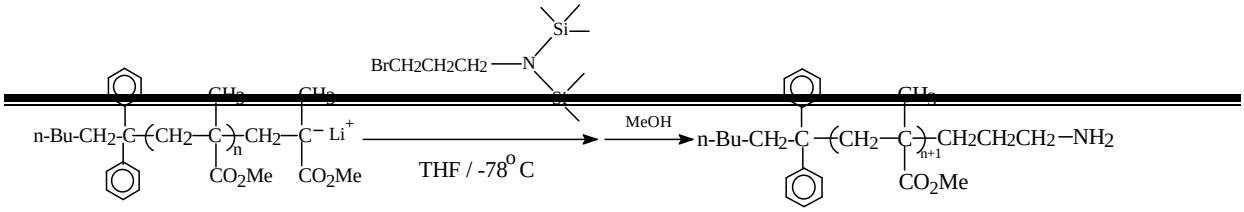
reacting with the electrophile. An additional complication arises due to competing termination reactions, leading to loss of active chain ends.

In spite of these limitations, several attempts are reported in the literature for the synthesis of end-functionalized polymers by LAP[4], ATRP[3a, 5] and GTP[6]. To obtain high efficiencies of functionalization, each method has to be carefully optimized in terms of the choice of the initiator and the polymerization conditions.

There are only few reports of amine end functional poly (methyl methacrylate) s (PMMA's) in the literature. Amine end-functional polymers are of interest in several applications[7a-e]. They can be used as an initiator for the synthesis of polypeptide block copolymers[7a-7d].

Preparation of amine-terminated polymers by LAP invariably involve a post polymerization procedure to convert the end group into an amine group[8]. 1-[4-[*N*, *N*-bis (trimethylsilyl) amino] phenyl]-1-phenylethylene and 1-(dimethylaminophenyl)-1-phenylethylene were used to prepare amine-terminated polymers[8f-g] by living anionic polymerization. Nakahama et al reported high yields (96-100%) of primary amine functionalized polystyrene by reacting polystyryllithium with 1.5-2 equivalents of the protected amine, namely, N-(benzylidene)-trimrthylsilyl amine in benzene at 25^{o}C [8h]. In similar fashion primary amine terminated polystyrene have been prepared by the reaction of polystyryllithium with the product of reaction of methoxyamine and methyllithium at low temperature[8i].

More recently, Mays and coworkers reported[9] the synthesis of amine-terminated PMMA (Scheme 5.1) with M_n = 3.5x10^3 g/mol and M_w/M_n = 1.08 by reacting the living anionic chain end with an eletrophile, namely, 1-(3-bromopropyl)-N, N-(trimethylsilyl) amine in THF at -78^{o}C, in high yields. MALDI-ToF-MS of the amine-terminated PMMA and polystyrene confirmed efficient chain termination reaction.



Scheme 5.1. Amine-terminated PMMA via LAP

Amine-terminated PMMA with $M_{n,\ SEC}$ = 7750-66000 g/mol were prepared by atom-transfer radical polymerization (ATRP) using CuBr/N, N, N', N'', N''-pentamethyldiethylenetriamine (PMDETA) and with protected amine functional group bearing initiator[10a]. However, under these conditions polymerization proceeds in an uncontrolled fashion. PMMA's with M_w/M_n = 1.53-2.86, initiator efficiency in the range of 1.06 to 0.17 and conversions in the range of 22-98% were obtained. In another approach, halogen end functional poly (acrylate) s prepared by ATRP was converted to the corresponding azide by nucleophilic displacement using NaN_3/DMF. The azide terminated acrylate polymer was further converted to phosphoranimines, which upon hydrolysis gave amine-terminated poly (acrylate) s[10b].

Dimethylamino-functionalized PMMA with $M_{n,\ SEC}$ = 2200-2500, M_w/M_n = 1.06-1.07 and F_n in the range of 0.93-0.90 was prepared using GTP[11] by the reaction of the living trimethylsilyl ketene acetal-ended PMMA with methyl *E*-3-(2-dimethylaminophenyl)-2-phenylacrylate (AMPA) using tris (dimethyl amino) sulfonium bifluoride ($TASHF_2$) at room temperature.

As a part of our studies aimed at exploring the scope of eletrophilic termination approach of GTP chain ends for the synthesis of end functional PMMA's, we herein report the preparation of amine terminated PMMA via GTP by the reaction of the silyl ketene acetal chain end of PMMA with N-trimethylsilyl benzaldimine. Silyl ketene acetals are reported to undergo facile reaction with aldimines to generate the desired amino functionality in good yields[12]. The efficiency of polymer functionalization was examined using ^{1}H NMR, SEC and MALDI-TOF methods.

5.2 Experimental Methods

5.2.1 Materials

Diethyl ether (S.D. Fine Chemicals, Mumbai) was distilled over Na-benzophenone. ZnI_2 (99%, Aldrich, USA, 100-mesh) and tetra-n-butyl ammonium bibenzoate TBAF (1.0 M in THF, Aldrich, USA) were used as received. N-trimethylsilyl banzaldimine prepared according to reported procedure[12a]. Tetra-n-butyl ammonium bibenzoate (TBABB) prepared according to

procedure reported elsware[13]. MeOH and t-BuOH (S.D. Fine Chemicals, Mumbai) dried and degassed before use.

Preparation of N-trimethylsilyl benzaldimine (3)

A flame dried 50 mL round bottom flask was charged with lithium hexamethyldisilazide (14.5 g, 0.0866 mols) inside a glove box. The flask was cooled to 0^{o}C and dry THF (80 mL) was added. To this was added benzaldehyde (8.8 mL, 0.0866 mols) drop-wise. The resulting solution was stirred for 30 minutes at 0^{o}C. Thereafter, trimethylsilylchloride (11 mL, 0.0866 mols) was added in one portion and stirring continued for 30 minutes at 0^{o}C. The reaction mixture was warmed to room temperature and subjected to fractional distillation (55-60^{o}C/0.05 mm Hg) yielding 13.8 g (90%) N-trimethylsilyl benzaldimine as pale green oil. The product was highly sensitive to oxygen and moisture and was therefore stored under nitrogen at 10^{o}C.

^{1}H NMR ($CDCl_3$/200 MHz): δ 0.25 (s, 9H, $SiMe_3$), 7.4 (m, 3H, ArH), 7.7 (m, 2H, ArH), 8.93 (s, 1H, CH=N)

5.2.2 Model reaction between MTS (2) and N-trimethylsilyl banzaldimine (3) using ZnI_2 in THF.

A flame dried 50 mL round bottom flask was charged with dry ZnI_2 (0.35 g, 1.15x10^{-3} mol) inside a glove box. THF (20 mL) was added to the flask. N-trimethylsilyl benzaldimine (0.2 g, 1.15x10^{-3} mol) was added and stirred for 5 minutes. MTS (0.3 mL, 1.15x10^{-3} mol) and Bu^{t}OH (0.1 mL, 1.15x10^{-3} mol) were added under nitrogen atmosphere in rapid succession and stirred at room temperature for 3 h. The crude product was washed with water and dried over Na_2SO_4. Purification using column chromatography yielded the amino-ester as a light yellow liquid in ≥ 93% isolated yield

5.2.3 Synthesis of amine-terminated PMMA by GTP

A clean and flame dried two neck 250 mL reactor, equipped with a nitrogen inlet by means of three way septum adapter, a dropping funnel and a magnetic stir bar was charged with 1.2 mg of TBABB catalyst (2.35x10^{-6} mol, 0.1mol% of MTS) in THF (1 mL), followed by dry THF

(30 mL) was transferred using a canula under positive pressure of dry nitrogen. MTS (0.5 mL, $2.35x10^{-3}$ mol) was added using syringe at room temperature. After 5 minutes, 5.0 mL of MMA (0.047 mol) was added using dropping funnel at approx. 1mL/min. The polymer solution was then added to 0.42 g of N-trimethylsilyl benzaldimine ($2.35x10^{-3}$ mol) activated by $2.35x10^{-3}$ mol of ZnI_2 (0.7508 g) in THF followed by immediate addition of 0.23 g of t-BuOH ($2.35x10^{-3}$ mol). The reaction was allowed to continue for 12 h at room temperature. Later, subsequently, $2.35x10^{-3}$ mol of NBu_4F/methanol was added to the reaction mixture and reaction was continued for overnight at 25^{o}C and the resulting reaction mixture was precipitated in hexane.

The polymer solution was passed through neutral alumina and precipitated in hexane to obtain pure colorless polymer free of ZnI_2. The polymer was further purified by reprecipitating it from THF solution using excess hexane. The obtained polymer was dried at 60^{o}C in vacuum. Yield: 5.2 g (100 %).

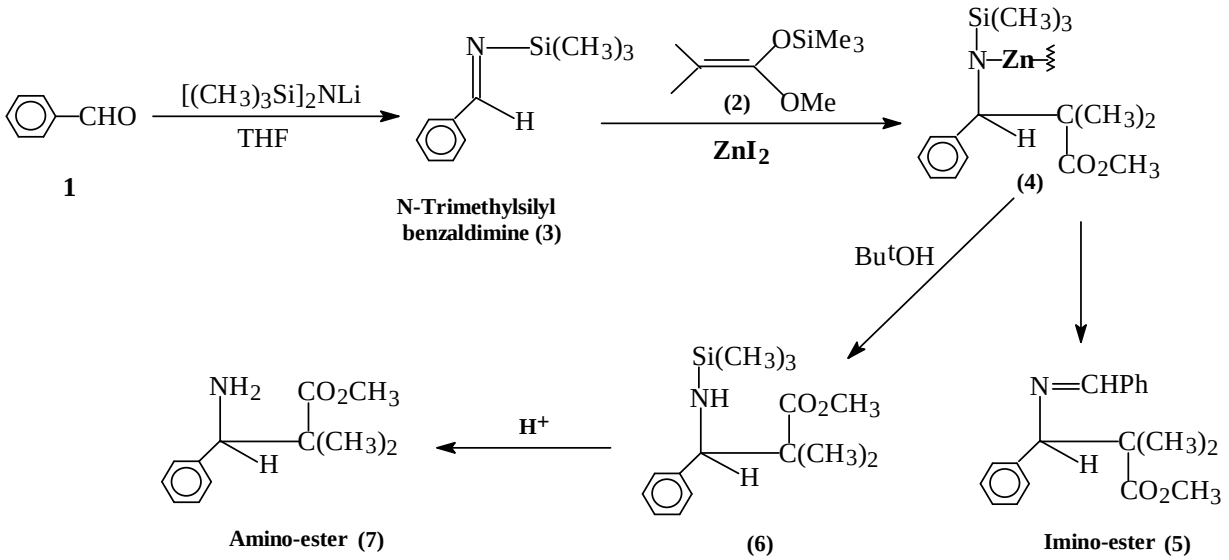
5.2.4 Characterization

The methods of characterization are described in chapter 2.

5.3 Results and Discussion

5.3.1 Model reaction between MTS and N-trimethylsilyl benzaldimine

To arrive at the most suitable conditions, initially model reactions were carried out between MTS (**2**) and N-trimethylsilyl benzaldimine (**3**) using 1.0 equivalent of ZnI_2 based on MTS. Immediate addition of t-BuOH was necessary to avoid the formation of imino-ester (**5**) (Scheme 5.2).



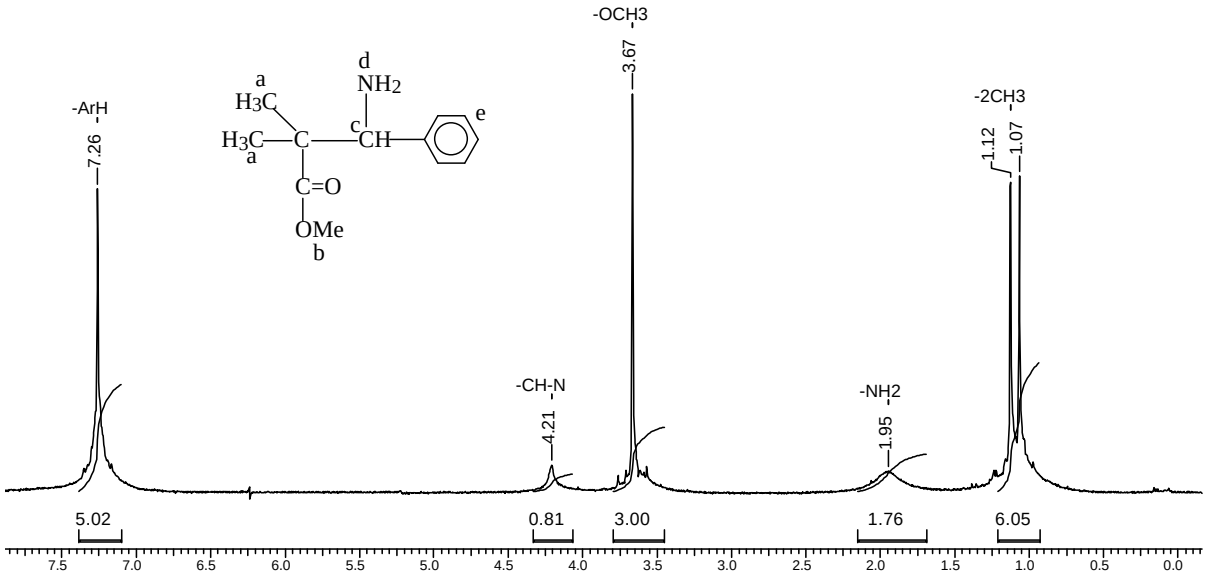
Scheme 5.2. Reaction between MTS and N-trimethylsilyl banzaldimine

In the absence of t-BuOH, imino-ester is reported to form as the sole product due to competitive trans-amination between unreacted imine and a metallo-amide intermediate[12a]. The results are shown in table 5.1. The reaction is equally efficient in THF and diethyl ether as solvents.

Table 5.1. Reaction between MTS and N-TMS benzaldimine at 25^0C

Entry	N-TMS benzaldimine, mmol	ZnI_2, mmol	^{t}BuOH, mmol	MTS, mmol	Solvent, mL	Time, h	Isolated Yield (β-amino ester) %
1	1.15	1.15	1.15	1.15	Diethyl ether, 10	3	98
2	1.15	1.15	1.15	1.15	THF, 10	3	93

FIG 5.1 SHOWS THE ^{1}H NMR SPECTRUM OF B-AMINO ESTER (7),



WHICH SHOWED A BROAD PEAK AT Δ 1.95 CORRESPONDING TO TWO PROTONS OF THE AMINO GROUP.

Fig 5.1. ^{1}H NMR spectrum of β-aminoester (**7**) in $CDCl_3$ (200 MHz)

Fig 5.2 shows the ^{13}C NMR spectrum of β-amino ester (**7**) exhibiting peaks at δ 19.29 ($2CH_3$) at δ 51.67 ($-OCH_3$), at δ 61.71 (CH), at δ 127.65 (Ar-C), and at δ 177.57 (>C=O). The diastereotopic methyl groups could not be distinguished. FT-IR of β-aminoester (**7**) shows peaks at 1728 cm^{-1} for the ester group and at 3388 cm^{-1} for NH group.

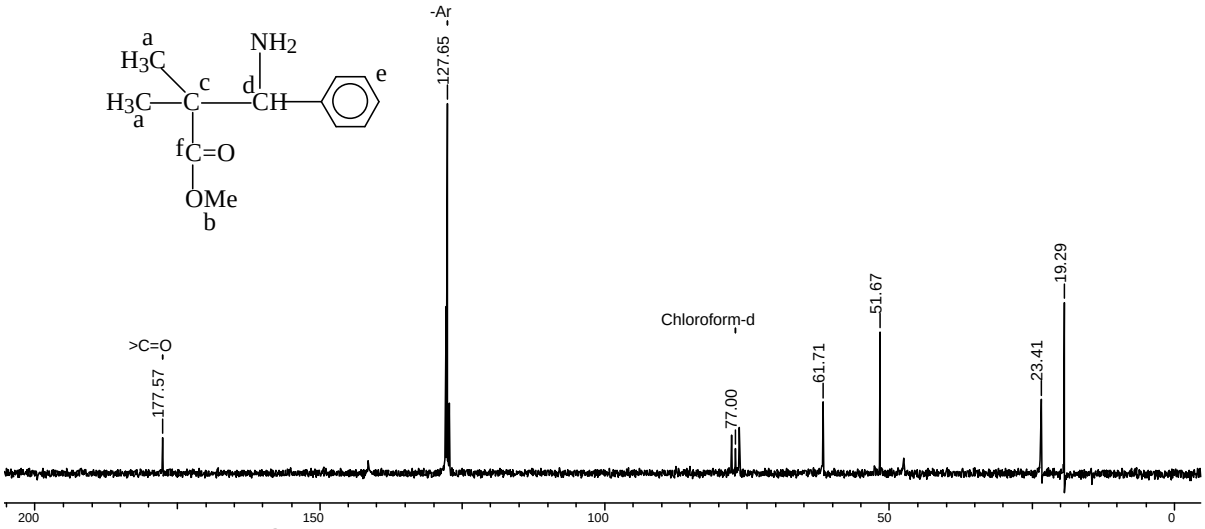
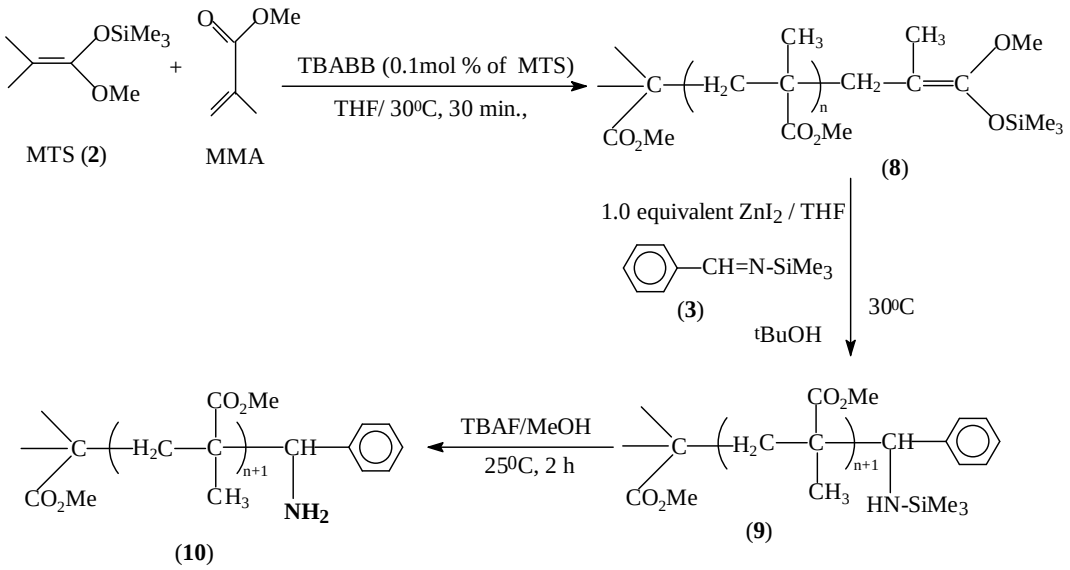


Fig 5.2. ^{13}C NMR spectrum of β-amino ester (**7**) in $CDCl_3$ (50 MHz)

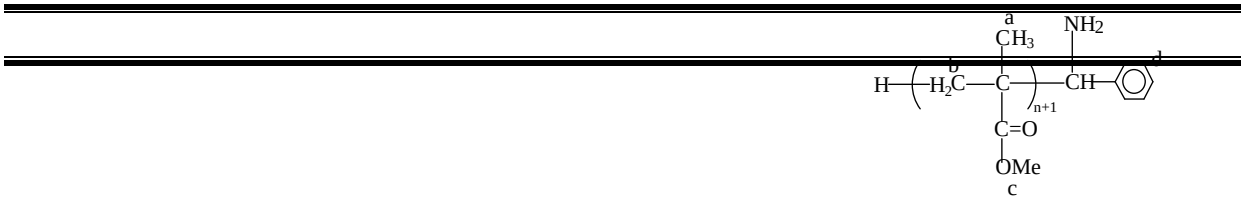
5.3.2 AMINE-TERMINATED POLY (METHYL METHACRYLATE) S VIA GTP

THE GTP OF MMA WAS CARRIED OUT USING MTS (2) AS INITIATOR IN THF AT 30^{O}C USING A NUCLEOPHILIC OXYANION CATALYST, TBABB (01 MOL% BASED ON MTS). LIVING TRIMETHYLSILYL KETENE ACETAL-ENDED PMMA (8) WAS TERMINATED USING N-TRIMETHYLSILYL BENZALDIMINE (3) AND 1 EQUIVALENT OF ZNI_2 AS LEWIS ACID CATALYST IN THF RESULTING IN THE AMINE-TERMINATED PMMA (10) (SCHEME 5.3).



Scheme 5.3. Amine-terminated PMMA's via GTP

Narrow molecular weight amine-terminated PMMA's oligomers were prepared with initiator efficiencies in the range of 0.84-1.06. The number average degree of functionality (F_n) was found to be between 0.80-0.85 (table 5.2). A typical ^{1}H NMR of amine-terminated PMMA in acetone-d_6 is shown in figure 5.3 (entry 1, table 5.2). M_n was calculated from the NMR spectra by comparing the ratio of aromatic protons (at δ 7.4 ppm) with that of $-OCH_3$ protons (at δ 3.6 ppm) of PMMA.



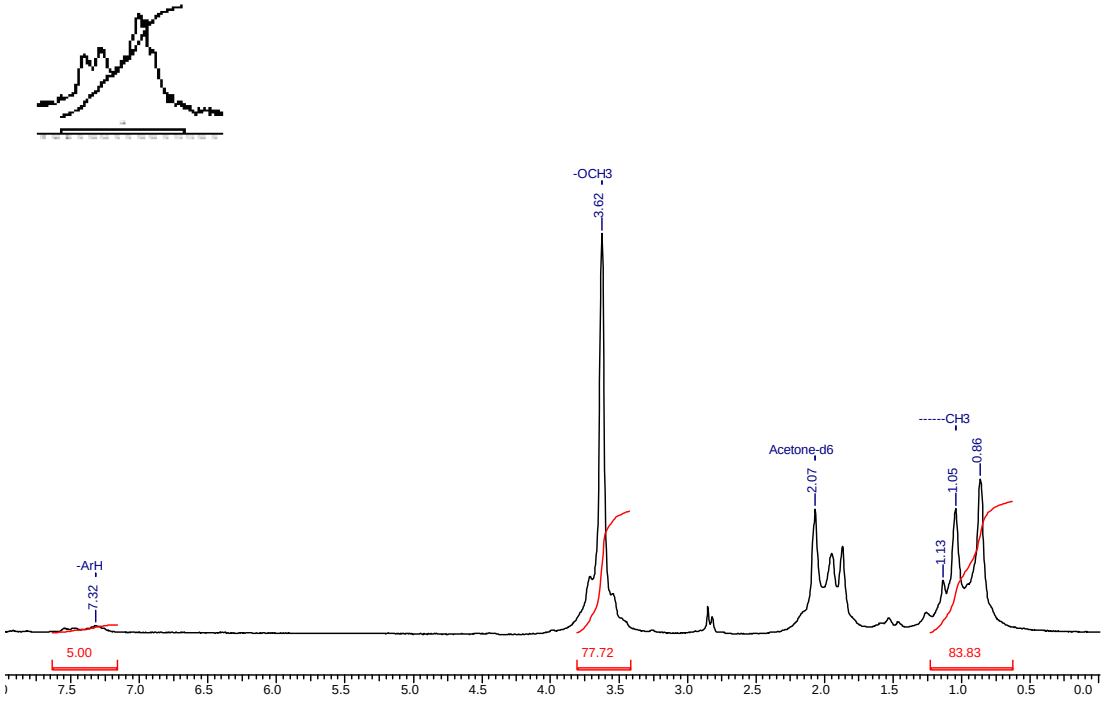


Fig 5.3. ^{1}H NMR spectrum of amine-terminated PMMA (entry 1, table 5.2) in acetone-d_6 (200 MHz)

Figure 5.4 shows ^{13}C NMR spectrum of amine-terminated PMMA's (entry 1, table 5.2) in acetone-d_6.

Table 5.2. Synthesis of amine end-functional poly (methyl methacrylate) by GTP

Entry	MMA[a], mol	MTS, mol x 10^3	THF, mL	TBABB, mol x 10^6	N-TMS Benzaldimine, mol x 10^3	ZnI_2, mol x 10^3	^{t}BuOH, mol x 10^3	M_n (theory), g/mol	M_n (SEC), g/mol	M_w/M_n (SEC)	M_n (VPO), g/mol	M_n (NMR) g/mol	$I^b_{efficiency}$	F^c_n
1	0.047	2.35	30	2.35	2.35	2.35	2.35	2100	2205	1.07	2400	2600	0.95	0.85
2	0.047	1.56	30	1.56	1.56	1.56	1.56	3100	3200	1.11	2800	4000	0.97	0.80
3	0.047	2.35	30	2.35	2.35	2.35	2.35	2100	2525	1.09	2800	3155	0.84	0.80
4	0.047	1.56	30	1.56	1.56	1.56	1.56	3100	2905	1.09	3200	3418	1.06	0.85

a: $[MMA]_0 = 1.56$ mol/L

b: $I_{efficiency} = M_n$ (theory)/M_n (SEC)

c: $F_n = M_n$ (SEC)/ M_n (NMR)

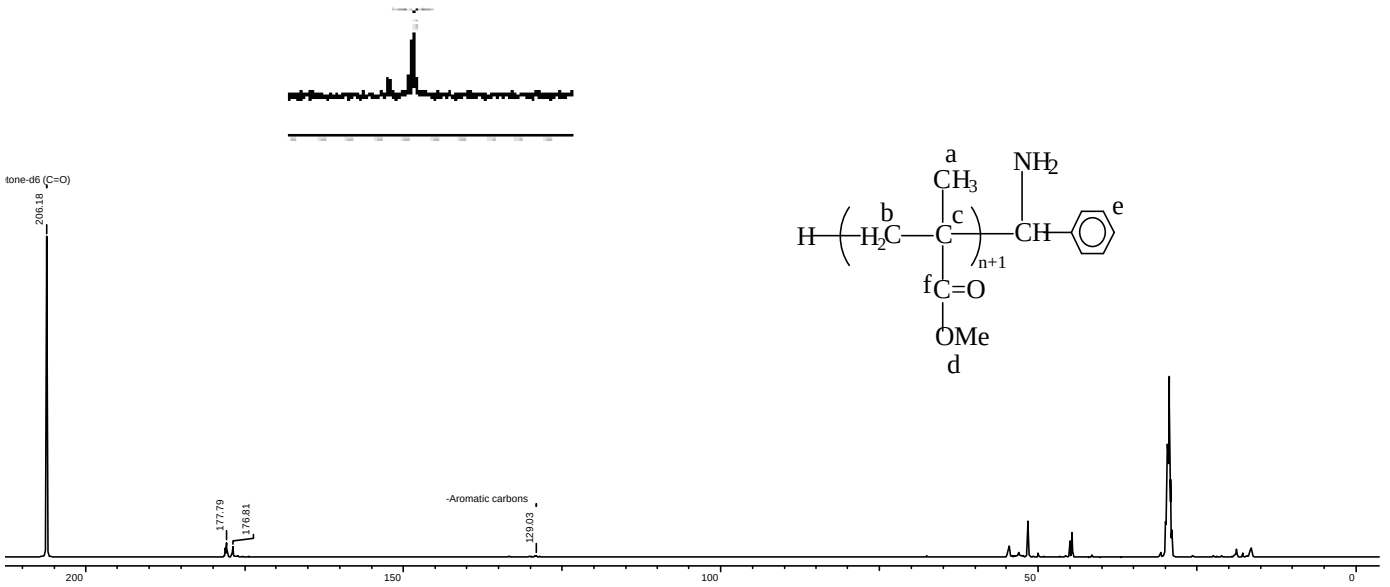


Figure 5.4. ^{13}C NMR spectrum of amine-terminated PMMA (entry 1, table 5.2) in acetone-d_6 (50 MHz)

The SEC trace of amine-terminated PMMA (Figure 5.5) (entry 1, Table 5.2) shows a less intense UV-response (due to low concentration of aromatic end-group) at the same elution volume/time of that of RI response indicating the presence of aromatic group at the chain-end.

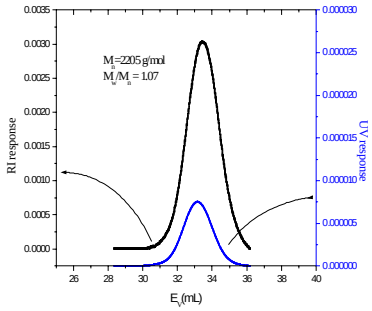
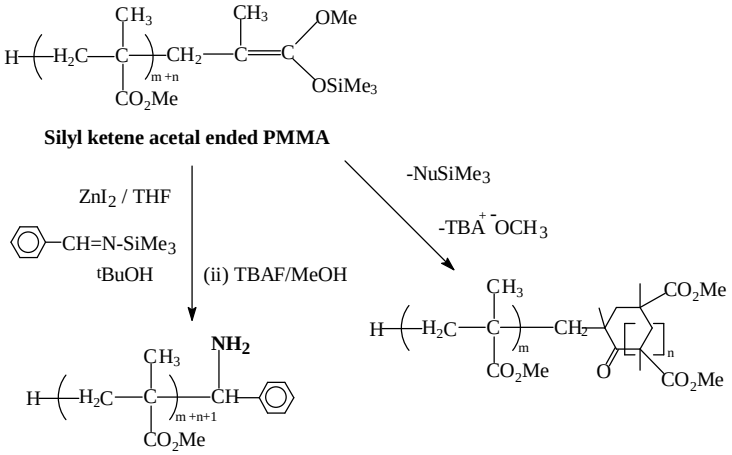


Fig 5.5. SEC trace of amine-terminated PMMA (entry 1, table 5.2)

MALDI-ToF-MS spectrum of amine-terminated PMMA was performed by dissolving the polymer in THF (3 mg/mL) and mixed with the matrix 2,5-dihydroxybenzoic acid (10 mg/mL solution in THF) in a 1:1 proportion. For enhancement of ion formation, a small amount of LiCl was added to the solution. After depositing 0.5 μL of the solution on the sample holder the solvent was evaporated in hot air. MALDI-ToF spectrum of amine-terminated PMMA is shown in figure 5.6 (entry 1, table 5.2) in which the mass peaks correspond to the $[M+Li]^+$ *= 100.12 (MMA) * n (DP) + H (1.0079) + Ar-CH-*NH_2 *(106.1476) +* Li^+*(6.941) for e.g. n= 20 gives* M_n*= 2116.4965 g/mol i.e., expected series of major fraction will be 2116.4965, 2216.6165, 2316.7365…….. etc. MALDI ToF exhibited a major series (figure 5.6) as 2109.28, 2209.22, …….etc with Δ= 7 Da. Additionally, low intensity peaks attributed to an oligomer series with cyclic end groups* $[M+Li]^+$ *= 100.12 (MMA) * n (DP) + H (1.0079) -* OCH_3 *(31) + 6.9(Li) for e.g. n= 20 gives* M_n *=1979.3147 g/mol i.e., series of lower fraction will be 1979.3147, 2079.4347, 2179.5547……..etc. were also observed at mass numbers 1979.21, 2078.86……..etc.*

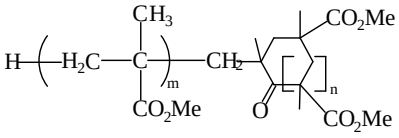
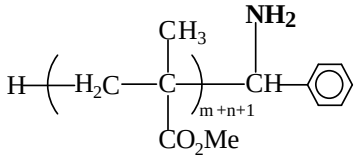
Since strong evidence is now present for a dissociative anionic process for GTP[2], the second smaller homologous series (with mass difference between both homologous series is about 31 g/mol due to loss of – OCH_3 *group as a result of backbiting reaction) must be attributed to the formation of cyclic structure in addition to linear fractions (Scheme 5.4). As the mass increment of both homologous series is the same (i.e. about 100 g/mol of MMA), the change in the chemical structure must be attributed to variations in the end-group.*



Scheme 5.4. Formation of cyclic fraction along with amine-terminated PMMA

The fact that both homologous series have their maximum abundance at about 2200 g/mol indicates that they are formed simultaneously in the reaction.

Table 5.3. Different observed series in MALDI ToF MS of amine end-functional PMMA[a] prepared by GTP

Polymer	*End group*	*Observed series[b]*
	*Cyclohexanone end group with n =1 i.e. loss of –OCH_3 from linear fraction*	*1979.21, 2078.86,….*
	*106.1476 (Ar-CH-NH_2)-amine end group*	*2109.28, 2209.22,…etc with Δ= 7 Da*

a: Matrix is 2,5-dihydroxybenzoic acid (F.W: 154.13) with Li+ (LiCl salt)

*b: $[M+Li]^+$ = 100.12 (MMA) * n (DP) + H (1.0079) + Ar-CH-NH_2 (106.1476) + Li^+(6.941)*

This is in accordance with the observation that the living nature of GTP depends on the nature and concentration of catalyst[2] and also on molar mass of the polymer. Here we used 0.1 mol% of less nucleophilic TBABB catalyst to keep low cyclic fraction. Different observed series in MALDI ToF of amine end-functional PMMA prepared by GTP is shown in table 5.3.

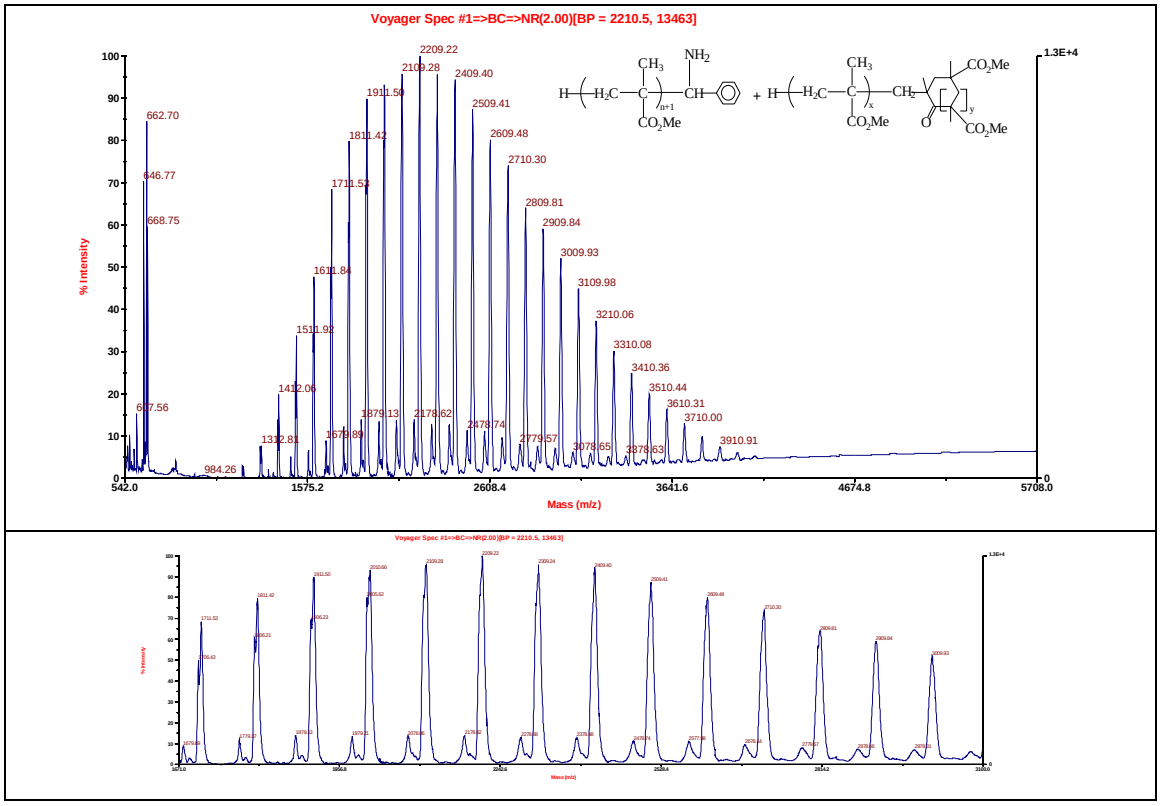


Fig 5.6. MALDI-ToF spectrum of amine-terminated PMMA prepared by GTP using TBABB catalyst for silyl ketene acetal ended PMMA and Lewis acid ZnI_2 for functionalization reaction at room temperature (entry 1, table 5.2). $[M+Li]^+$ = 100.12 (MMA) * n (DP) + H (1.0079) + Ar-CH-NH_2 (106.1476) + Li^+(6.941). (Matrix: Dihydroxybenzoic acid and LiCl for enhancement of ion formation) (Δ= 7 Da)

5.4 Conclusions

Narrow molecular weight amine-terminated poly (methyl methacrylate) s were prepared by group-transfer polymerization with initiator efficiencies in the range of 0.84-1.06 and narrow molecular weight distributions (M_w/M_n = 1.07-1.11). The number average degree of functionalization as determined by NMR/SEC was in the range of 0.80-0.85. MALDI-ToF-MS analysis of amine functionalized PMMA provide evidence for competing chain end cyclization.

High concentration of Lewis acid catalyst (ZnI_2) and long reaction time may result in increased occurrence of cyclization reaction.

5.5 References

1. (a). Jerome R.; Teyssie PH.; Vuillemin B.; Zundel T.; Zun C *J Polym Sci, Polym Chem.*, **1999**, 37, 1. (b). Baskaran D *Prog. Polym. Sci.*, **2003**, 28, 521.

2. Webster O. W Adv Polym Sci ***2004***, *167, 1.*

3. (a). Matyjaszewski, K.; Xia, J *Chem. Rev.* **2001**, 101, 2921. (b). Hawker, C. J.; Bosman, A.W.; Harth, E. *Chem. Rev* **2001**, 101, 3661. (c). Chiefari, J.; Chong, Y. K. B, Ercole, F.; Krstina, J.; Jeffery, J.; Letp, T.; Mayadunne, R. T. A.; Meijs, G. F.; Moad, C.L.; Moad, G.;
Rizzardo, E.; Thang, S. H. *Macromolecules* **1998**, 31, 5559. (d). Mayadunne, R.T.A.; Rizzardo, E.; Chiefari, J.; Chong, Y.K.; Moad, G.; Thang, S. H *Macromolecules* **1999**, 32,
6977.

4. (a) Hirao, A.; Hayashi, M *Acta Polym*. **1999**, 50, 219. (b) Patil, A.O.; Schulz D.N.; Novak B. M *Functional Polymers*, *ACS Symposium series*, **1998**, 704.

5. Coessens, V.; Pintauer, T.; Matyjaszewski, K. *Prog. Polym. Sci*. **2001**, 26, 337.

6. Sogah, D.Y.; Hertler, W.R.; Webster, O.W.; Cohen, G. M. *Macromolecules* **1987**, 20,1473.

7. (a). Schlaad, H.; Antonietti, M. *Eur. Phys. J. E*, **2003**, 10, 17. (b). Orr, C. A.; Cernohous, J. J.; Guegan, P.; Hirao, A.; Jeon, H. K.; Macosko, C. W. *Polymer*, **2001**, 42, 8171. (c). Dadmun, M. D.; Mays, J. W.; Kilbey, M.; Smith, G.; Advincula, R. C. *Polymer Preprints*, **2005**, 46, 420. (d). Klok, H. A.; Lexommandoux, S. *Adv. Mater*. **2001**, 13, 1217. (e). Pantazis, D.; Schulz, D. N.; Hadjichristidis, N. *J. Polym. Sci. Part A: Polymer Chemistry*, **2002**, 40, 1476.

8. (a). Ueda, K.; Hirao, A.; Nakahama, S. *Macromolecules*, **1990**, 23, 939. (b). Kukula, H.; Schlaad, H.; Falkenhagen, J.; Kruger, R-P. *Macromolecules*, **2002**, 35, 7157. (c). Cernohous, J. J.; Macosko, C. W.; Hoye, T. R. *Macromolecules*, **1998**, 31, 3759. (d). Quirk, R. P.; Cheng, P. *Macromolecules* **1986**, 19, 1291. (e). Elkins, C. L.; Long, T. E. *Macromolecules*, **2004**, 37, 6657. (f). Quirk, R. P.; Lynch, T. *Macromolecules* **1993**, 26, 1206. (g). Quirk, R. P.; Zhu, L. Brit. *Polym. J*. **1990**, 23, 47. (h). Hattori, I.; Hirao,
A.; Yamaguchi, K.; Nakahama, S.; Yamazaki, N. *Macromol. Chem*. **1983**, 184, 1355. (i). Quirk, R. P.; Chen, P. L. *Macromolecules* **1986**, 19, 1291.

9. Ji, H.; Baskaran, D.; Mays, J. W. ACS Polymer Preprints, ***2005***, *46(2), 452.*

10. (a). V. B. Sadhu.; J. Pionteck.; D. Voigt.; H. Komber.; B. Voit Macromol. Symp. **2004**, 210, 147. (b). Coessens, V.; Nakagawa, Y.; Matyjaszewski, K. *Polym. Bull*. ***1998***, *40, 135.*

11. Quirk, R. P.; Ren J *Polymer International* **1993**, 32, 205.

12. (a). Colvin, E. W.; McGarry, D.; Nugent M. J. Tetrahedron ***1988,*** *44, 4157.*
(b). Loh, T.P.; Wei, L. L Tetrahedron Lett. ***1998***, *39, 323. (c). Manabe, K.; Mori Y.; Kobayashi, S* Synlett ***1999***, *9, 1401. (d). Akiyama, T.; Takaya, J.; Kagoshima, H* Synlett ***1999***, *9, 1426. (e) Chen G. M.; Brown H. C* J. Am. Chem. Soc ***2000***, *122, 4217. (f). Shimizu, M.; Itohara, S.; Emi, Hase.* Chem. Commun. ***2001***, *2318.*

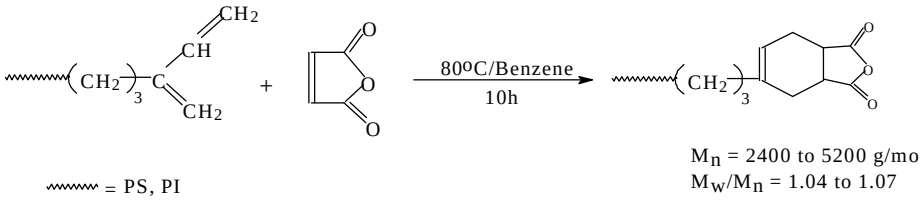
13. (a). Brittain, W. J. *J. Am. Chem. Soc*. 1988**, *110*, 7440. (b). Puranik, V. G.; Tavale, S.**

S.; Iyer, V. S.; Sehra, J. C.; Sivaram, S. ***J. Chem. Soc., Perkin Trans. 2*** 1993**, 1517.**

Chapter 6: Attempted Synthesis of Anhydride End-functional Poly (methyl methacrylate) s via Group Transfer Polymerization

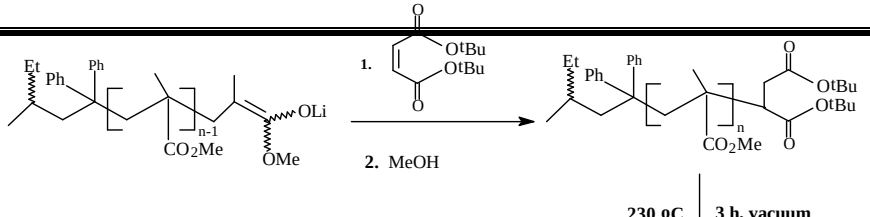
6.1 Introduction

Anhydride end-functional polymers are a class of useful functional polymers that find applications in reactive polymer blending which is a widely used compatibilization method used for immiscible polymer blends and for promoting adhesion between immiscible polymers[1]. Living anionic polymerization (LAP) has been the method of choice for the synthesis of polymers with terminal anhydride functionality. Takenaka et al synthesized[2] anhydride terminal polystyrenes and polyisoprene involving a Diels-Alder addition of maleic anhydride to a diene-terminated polymer (scheme 6.1).



Scheme 6.1. Anhydride terminal polystyrene and polyisoprene using LAP

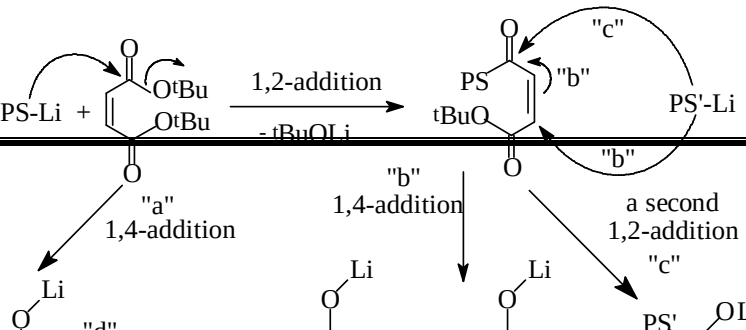
Macosko et al synthesized[3] anhydride-terminal poly (methyl methacrylate) (PMMA), polystyrene (PS), polyisoprene (PI), and poly (vinyl pyridine) (PVP) in the molecular weight



Scheme 6.2. Synthesis of polymers with a terminal anhydride group using LAP

range M_n = 15,800 g/mol to 51,300 g/mol (PDI = 1.03 to 1.22) with a high functionality (F_n>0.95) by reacting the chain end with di-tert-butyl maleate followed by hydrolysis and condensation to the corresponding anhydride (scheme 6.2).

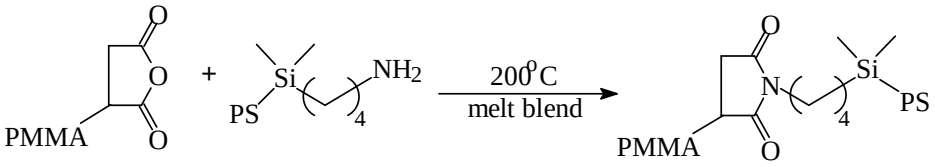
When a polystyryllithium (PSLi) (Mn=17,500) was allowed to react with di-tert-butyl maleate the GPC trace of the resulting polymer exhibited bimodal distribution with the high molecular weight peak having twice the intensity that of the low. Macosko ascribed this to a competition between 1,4-and 1,2-addition (scheme 6.3). If PSLi first reacts with the ester group in a 1,2-fashion, the resulting adduct still possesses a very reactive site towards 1,4-addition by another PSLi resulting in a bimodal distribution of molecular weights[3]. Chain coupling reaction did not occur[3] when polymerization was performed in THF at –80°C. The polymers obtained had a high degree of functionality ($F_n \geq 0.94$) and narrow molecular weight distributions.



Scheme 6.3. Polystyryllithium reaction with di-tert-butyl maleate

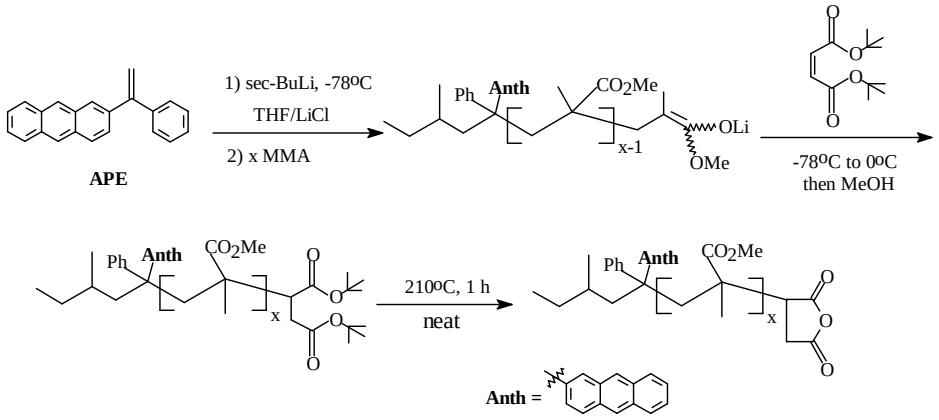
Presence of polar additive tetramethylethylenediamine (TMEDA) reduced the amount of 1,2-reaction. Organozinc compounds also promoted exclusively 1,4-conjugate addition[4]. TMEDA and solid zinc iodide were added to the PSLi. The color of the cyclohexane solution slowly changed from the characteristic deep red of PSLi/TMEDA to a faint orange, consistent with a transmetalation process. Upon addition of maleate a polymer having high anhydride end functionality (F > 0.8) and a unimodal molecular weight distribution was observed.

The functionality of the PS and PMMA polymers (F_n > 0.95) was determined following derivatization reactions with various amines. NMR spectroscopy and GPC of the resulting amides permits quantification of the extent of functionalization. Upon melt blending at 200°C, an anhydride terminal PMMA (M_n = 29,000) with an amino terminal PS (M_n= 18,500) all of the monofunctional homopolymers were converted to PS-PMMA diblock within 20 minutes (scheme 6.4).



Scheme 6.4. Melt blending of anhydride terminated PMMA with amino terminated PS

Macosko also described[5] the synthesis of anthracene-labeled PS and PMMA (scheme 6.5) with a terminal anhydride group using *sec*-butyllithium/1-(2-anthryl)-1-phenylethylene (APE) as an initiator via LAP and demonstrated the ability to detect these polymers by fluorescence detector at a concentration of ~ 100 times lower than with RI detection in SEC.



Scheme 6.5. Synthesis of anthracene-labled poly (methyl methacrylate) with terminal anhydride.

These polymers could be reacted with amine-functional polymers by melt blending, and the reaction progress could be monitored by gel permeation chromatography coupled with fluorescence detection. This highly sensitive and selective detection methodology was also used to monitor the coupling reaction of Fluorescent PMMA anhydride with PS-NH_2 at a thin-film interface, which was otherwise difficult to detect by conventional methods.

Pionteck et al.[6] reported the preparation of anhydride-terminated polystyrene via ATRP. 4-(Bromomethyl) phthalic anhydride was used as a functional initiator. However the reaction led to a polymer (M_n = 7100 – 12000 g/mol) with high polydispersity (M_w/M_n = 1.31-1.42).

Reactions of cyclic anhydrides and their derivatives with nucleophiles such as carbanions, Grignard reagents, Wittig reagents, nitrogen nucleophiles, and oxygen nucleophiles are known in the literature[7]. It was therefore of interest to see whether a silyl ketene acetal, under suitable condition, could undergo nucleophilic addition to a cyclic anhydride. Such a reaction, if successful, could offer a convenient way of introducing an anhydride group at the terminal end of a PMMA chain. Unsymmetrical α,β-unsaturated cyclic anhydrides, namely, itaconic anhydride and citraconic anhydride as well as symmetrical anhydrides, namely, maleic anhydride and 2,3-dimethylmaleic anhydride were explored as electron acceptors. There is no prior literature on the reaction of silyl protected ester enolates with cyclic anhydrides. This chapter describes the result of this exploration.

6.2 Experimental methods

6.2.1 Materials

Calcium hydride (Aldrich), 1,2-Dimethoxy ethane (95%, Aldrich, USA) distilled over $LiAlH_4$. $TiCl_4$ (95%, Aldrich, USA) used as received. Itaconic anhydride (95%, Aldrich, USA) was recrystallised from dry diethylethter. Maleic anhydride (S.D. Fine Chemicals, Mumbai) was recrystallised from dry benzene. Citraconic anhydride (98%, Aldrich, USA) was distilled under vacuum (bp 93-94^oC/10 mmHg). 2, 3-Dimethylmaleic anhydride (97% Fluka, Switzerland) was recrystallised from dry chloroform.

6.2.2 Model reactions

6.2.2.1 Reaction between itaconic anhydride and MTS

A flame dried 50 mL round bottom flask was charged with 0.1525 g (0.246 mmol, 10 mol%) of $Yb(OTf)_3$ catalyst and 0.275 g (2.46 mmol) of itaconic anhydride. Dry CH_2Cl_2 or toluene (10 mL) was transferred using a canula under nitrogen and stirred for 5 minutes. Subsequently, 0.5 mL (2.46 mmol) of MTS was added and the reaction continued at 30^oC. The progress of reaction was monitoring by TLC.

The desilylation reaction was carried out using 1N HCl: THF (1:9) for 1 h at 30^oC. The formed diacid was (scheme 6.6) extracted into ethyl acetate and washed well

with water and dried over Na_2SO_4. After concentration of the organic layer, column chromatography (60-120-mesh silica gel, EtOAc / *n*-hexane as eluent) afforded diacid in high yields (Table 6.1).

Acid value of diacid: 511 mg KOH/gm of sample (theory = 538 mg KOH/gm of sample) (95% of theory) (Acid value = $56.1 \times V_{mL, KOH} \times N_{KOH} / W_g$
= 56.1x 7.4 x 0.06756 / 0.0549 g
= 511 mg KOH/ gm of sample)

FT-IR of diacid: 1730 cm^{-1} (Carboxylic acids: 1750-1690, C=O stretching)
3196 cm^{-1} (O-H stretching, 3400-2400)

6.2.2.2 Reaction between citraconic anhydride and MTS

A flame dried 50 mL round bottom flask was charged with 0.3101 g (0.5 mmol, 10 mol%) of $Yb(OTf)_3$ catalyst and 0.5 mL (5.0 mmol) of citraconic anhydride. Dry CH_2Cl_2 (20 mL) was transferred using a canula under nitrogen and stirred for 5 minutes. Subsequently, 1.0 mL (5.0 mmol) of MTS was added and the reaction continued at 30°C. The progress of reaction was monitoring by TLC.

$Yb(OTf)_3$ was filtered and dicholoromethane was removed under reduced pressure and product was dissolved in 20 mL THF. Water (2 mL) was added and THF solution was stirred for 1 h at 30°C. The 1,2-adduct formed (scheme 6.7) was dried over Na_2SO_4. After concentration of the organic layer, column chromatography (60-120-mesh silica gel, EtOAc / *n*-hexane as eluent) afforded 1,2-adduct in 80% yield (0.856 g) (Table 6.2).

6.2.2.3 Reaction between maleic anhydride and MTS

A flame dried 50 mL round bottom flask was charged with 0.0505 g (8.15×10^{-5} mol, 10 mol%) of $Yb(OTf)_3$ catalyst and 0.0799 g (8.15×10^{-4} mol) of maleic anhydride. Dry CH_2Cl_2 (10 mL) was transferred using a canula under nitrogen and stirred for 5 minutes. Subsequently, 0.2 mL (8.15×10^{-4} mol) of MTS was added and the reaction continued at 30°C. The progress of reaction was monitoring by TLC.

6.2.2.4 Reaction between 2,3-dimethylmaleic anhydride and MTS

A flame dried 50 mL round bottom flask was charged with 0.0119 g (2.46×10^{-2} mmol, 1 mol% based on MTS) of TBABB catalyst. Dry THF (10 mL) was transferred using a canula

under nitrogen followed by 0.5 mL (2.46 mmol) of MTS was added and stirred for 5 minutes. Subsequently, 0.3102 g (2.46 mmol) of 2,3-dimethylmaleic anhydride in 5 mL of THF was added and the reaction continued at 30°C. The progress of reaction was monitoring by TLC. The 1,2-adduct was formed in quantitative yield (0.7390 g, 100%).

6.2.3 Characterization

The methods of characterization have been described in chapter 2.

6.3 Results and discussion

6.3.1 Reaction between itaconic anhydride and MTS

Itaconic anhydride was found to undergo isomerization to citraconic anhydride upon addition of MTS. The isomerization is complete in about an hour. Figure 6.1 shows ^{1}H NMR spectrum of the isomerized product citraconic anhydride formed (crude) upon isomerization of itaconic anhydride (entry 1, table 6.1).

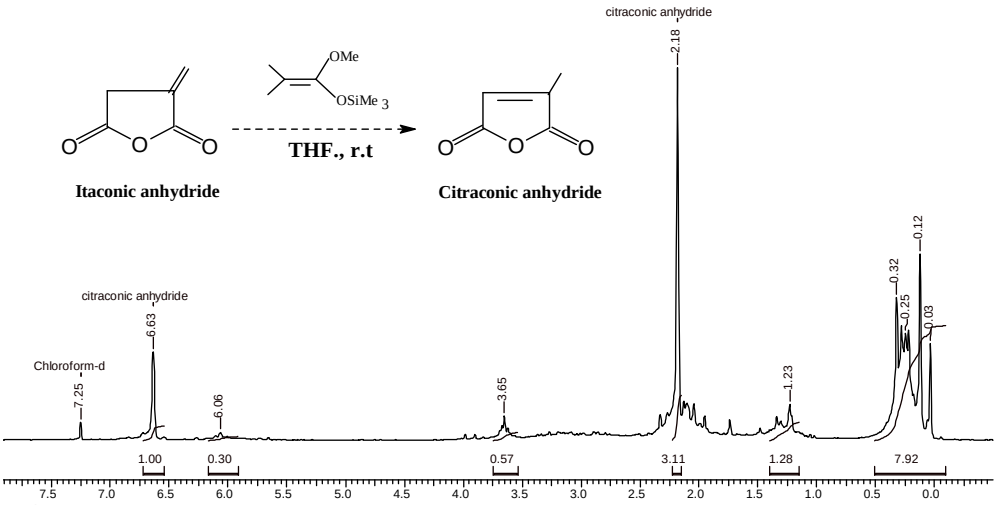
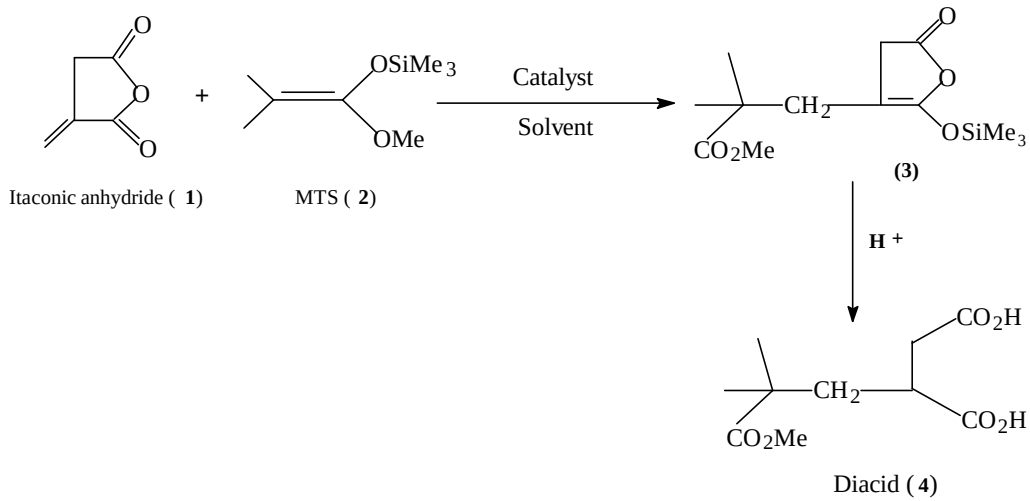


Fig 6.1 ^{1}H NMR spectrum of crude product (entry 1, table 6.1) in $CDCl_3$ (200 MHz)

FT-IR spectrum of crude product (entry 1, table 6.1) shows absorbance at 2958 cm^{-1} (due to methyl group); and at 3114 cm^{-1} (due to CH=), which is characteristic of citraconic anhydride. Itaconic anhydride is known to isomerize to citraconic anhydride by thermal (≥ 100 °C) [8] or in the presence of a base[9]. The extent of isomerization of itaconic anhydride to

citraconic anhydride was less in dichloromethane than in THF (entry 2, table 6.1). No isomerization is observed at –78°C in THF (entry 3, table 6.1). The precise mechanism of isomerization is not clear. It can be speculated that the small concentration of ester enolate present in equilibrium with the silyl ketene acetal, in a polar solvent, abstracts a proton α to the carbonyl, resulting in the more stable isomer.

Michael type reaction of MTS with itaconic anhydride (scheme 6.6) was studied with $Yb(OTf)_3$ as catalyst. It has been reported that strong Lewis acidity of dry $Yb(OTf)_3$ induces cationic ring-opening polymerization of THF[10]. Use of a hindered base such as 2,6 di-tert-butyl pyridine mitigates this problem.[11] Hence the reaction was studied in the presence and absence of 2,6-di-tert-butyl pyridine (entry 5, table 6.1).



Itaconic anhydride (**1**) MTS (**2**) Diacid (**4**)

Scheme 6.6. Reaction between itaconic anhydride and MTS

TABLE 6.1 REACTIONS BETWEEN ITACONIC ANHYDRIDE AND MTS

Entry	Itaconic anhydride mmol,	Catalyst 10mol%	Solvent	T(°C)	Time, minutes	Yield, %
1	2.46 (0.5g)	No catalyst	THF	30	40	33 dark brown
2	2.46	No catalyst	CH_2Cl_2	30	120	33 light brown
3	2.46	No catalyst	THF	-78	60	No reaction
4	2.46	$Yb(OTf)_3$	THF	30	30	90(**3**), 80(**4**)

5	2.46	$Yb(OTf)_3$	THF + 2,6 di-tert-butyl pyridine	30	20	85(**3**), 75(**4**)
6	2.46	$Yb(OTf)_3$	THF	10	30	95(**3**), 76(**4**)
7	2.46	$Yb(OTf)_3$	CH_2Cl_2	30	20	95(**3**), 90(**4**)
8	2.46	$Yb(OTf)_3$	Toluene	30	20	92(**3**), 89(**4**)
9	2.46	$Yb(OTf)_3$	DME	30	60	40(**3**)
10	2.46	$Yb(OTf)_3$	DME	50	60	60(**3**)

Order of addition: Itaconic anhydride + Lewis acid + solvent + MTS (1.1 equivalents)

The reaction between MTS and itaconic anhydride is exothermic (27°C to 36°C) at room temperature (entry 8, and 9, table 6.1). Figure 6.2 shows ^{1}H NMR spectrum of moisture sensitive silylether adduct of itaconic anhydride adduct (3). However, relative integration of number of protons in –OCH_3 and –$OSiMe_3$ was not in order.

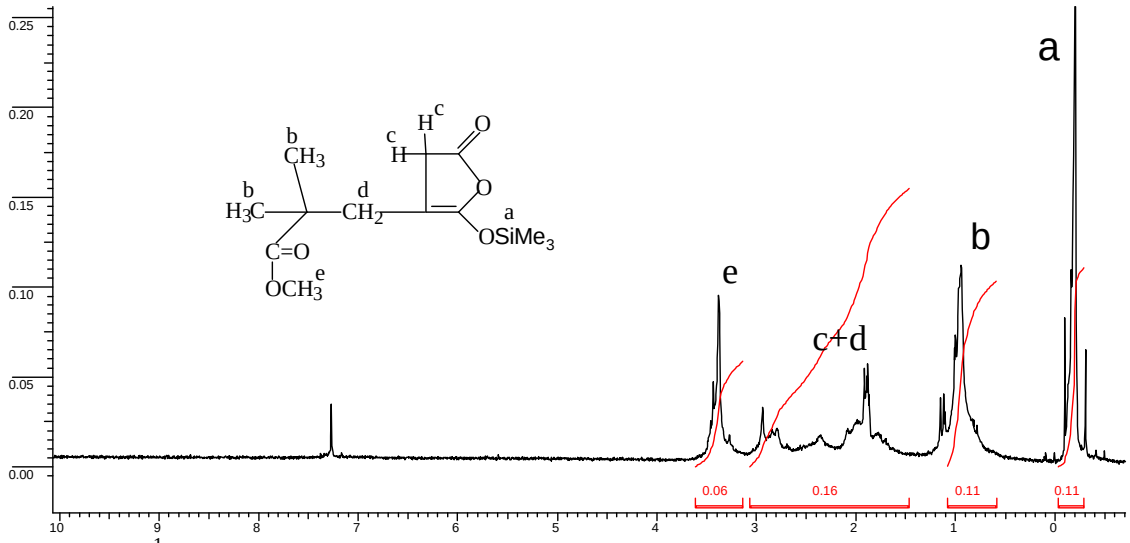


Fig 6.2. ^{1}H NMR spectra of silylether adduct of itaconic anhydride adduct **3** in acetone-d_6+$CDCl_3$ (200 MHz) (entry 8, table 6.1)

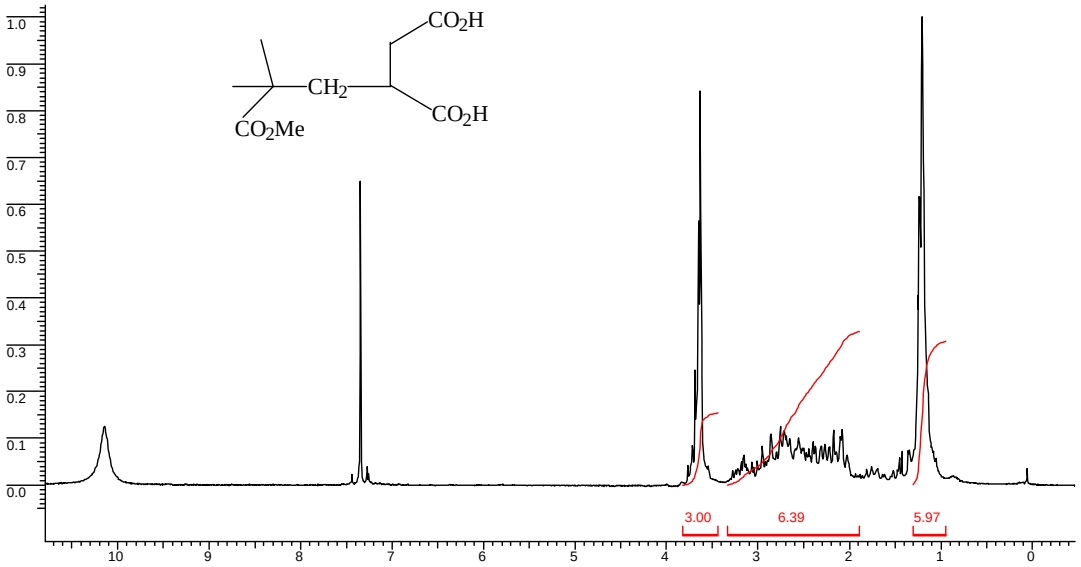


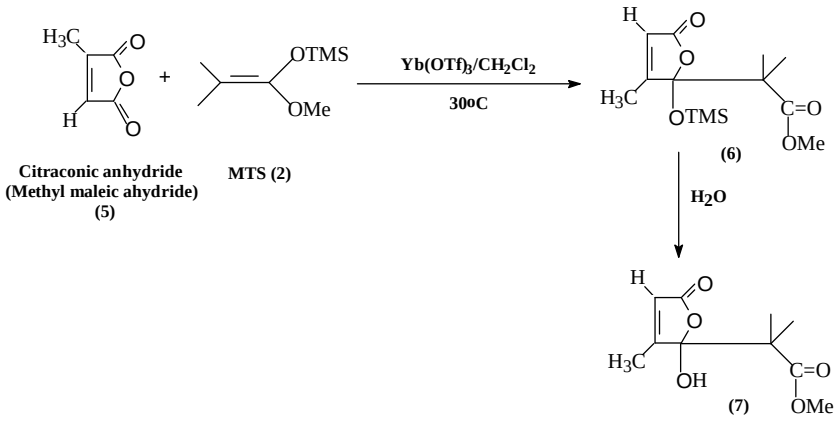
Fig. 6.3. ^{1}H NMR spectrum of diacid 4 in $CDCl_3$ + acetone-d_6 (200 MHz) (entry 8, table 6.1)

Upon column chromatography (ethyl acetate + petether) desilylation of 3 occurred and the dicarboxylic acid 4 is formed in ~90% yield. Figure 6.3 shows ^{1}H NMR spectrum of diacid 2 (entry 8, table 6.1), which is in accordance with the proposed structure.

The coordination of the Yb^{+3} ion to the lone pair of oxygen in 1, 2-dimethoxy ethane (DME) moderates the Lewis acidity of $Yb(OTf)_3$. Also, $Yb(OTf)_3$/DME is a heterogeneous system. Using DME as a solvent diacid **4** was isolated in relatively low yields (entry 9, and 10, table 6.1).

6.3.2 Reaction between citraconic anhydride and MTS

No reaction was observed between MTS and citraconic anhydride in THF at room temperature without a catalyst (entry 1, table 6.2). However, citraconic anhydride adds to MTS in a 1,2-fashion (scheme 6.7) using Lewis acid $Yb(OTf)_3$ (10 mol%) in dichloromethane at room temperature (entry 2, table 6.2).



Scheme 6.7 Reaction between citraconic anhydride and MTS

TABLE 6.2 REACTION BETWEEN MTS AND CITRACONIC ANHYDRIDE AT ROOM TEMPERATURE

Entry	MTS, mmol	Citraconic anhydride, mmol	Catalyst	Solvent, mL	Time, h	Yield
1	2.46	2.46	-	THF, 10	2	No reaction
2	5.0	5.0	Yb (OTf) 3 10 mol%	CH_2Cl_2, 20	2	80%

Upon column chromatography desilylation occurred and gave 1, 2-adduct (7) as the major product (80%). Fig 6.4 shows ^{1}H NMR spectrum of 7, which confirms the structure of 7.

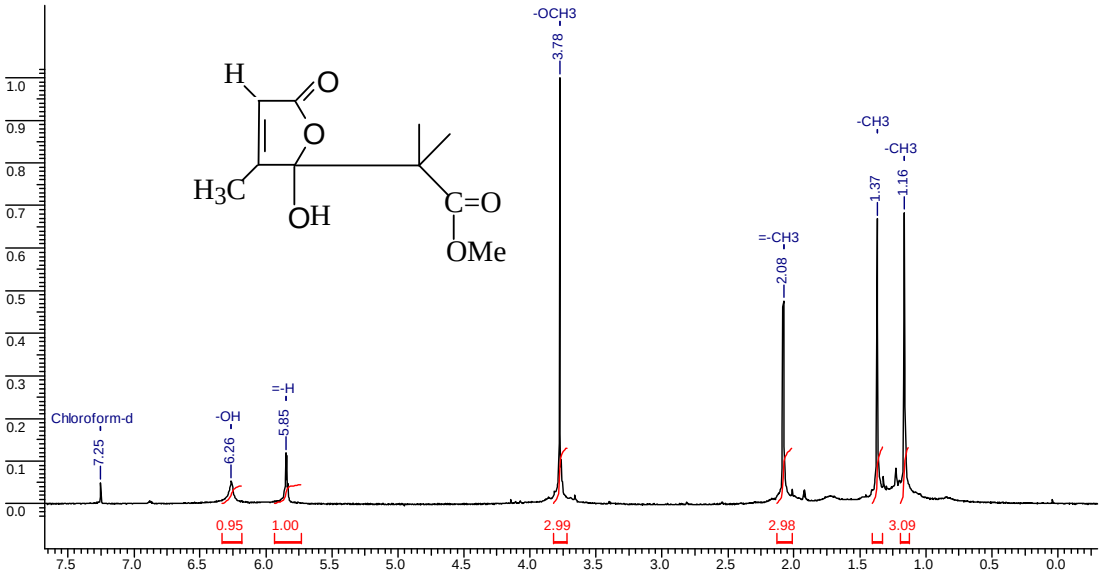


Fig 6.4. ^{1}H NMR spectrum of **7** in $CDCl_3$ (200 MHz) (entry 2, table 6.2)

The peak at 6.26 ppm corresponding to the hydroxyl proton disappears upon D_2O exchange (Fig 6.5).

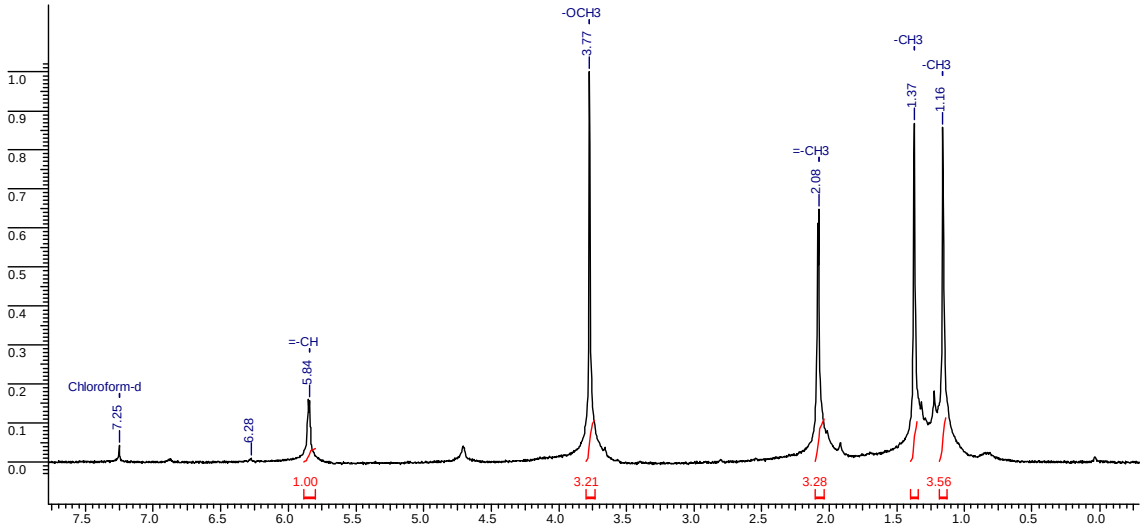
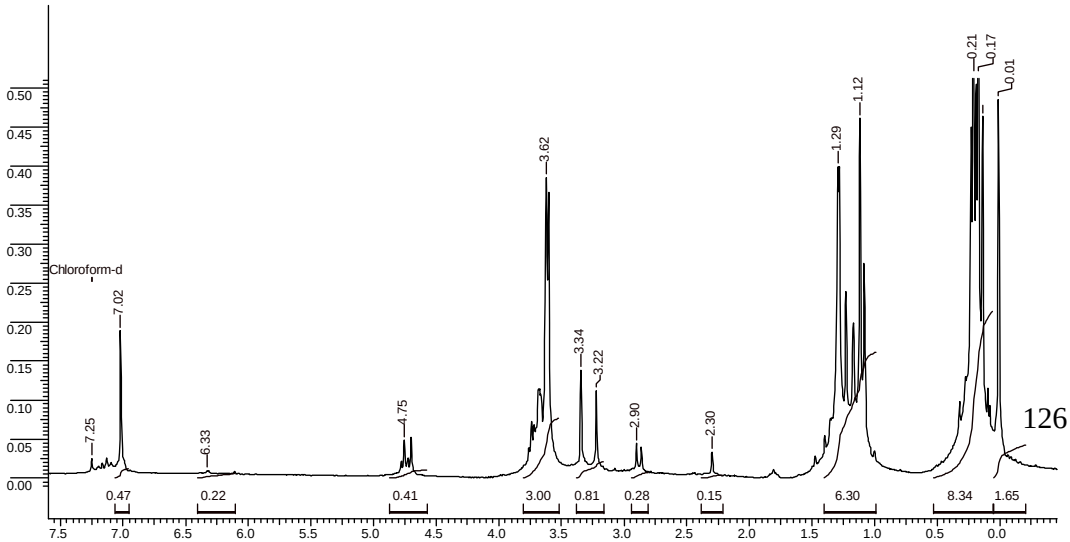


Fig 6.5. ^{1}H NMR spectrum of **7** in $CDCl_3$ (D_2O exchange) (200 MHz) (entry 2, table 6.2)

6.3.3 Reaction between maleic anhydride and MTS

When maleic anhydride is reacted with MTS in THF at 30^{o}C, an immediate exotherm is observed. The reaction temperature increases to 40 ^{o}C and stays at 40 ^{o}C for about 10 minutes. A brown color liquid is obtained which appears to be a complex mixture of products as evidenced by TLC.

Figure 6.6 shows ^{1}H NMR spectrum of the crude product of the reaction. The NMR spectrum is quite complex. Unreacted maleic anhydride is also seen (peak at 7.02 ppm). In spite of several attempts to examine differing reaction conditions, no single,



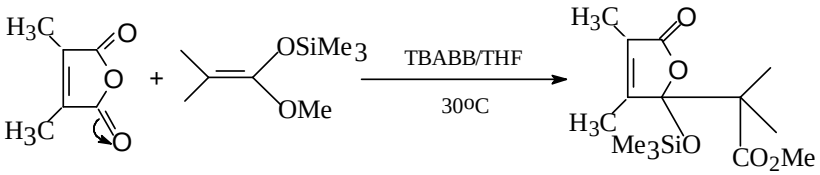
clean product could be isolated from this reaction. Hence, further study on this reaction was abandoned.

Fig 6.6 ^{1}H NMR spectrum of crude product in $CDCl_3$ (200 MHz)

We suspect that maleic anhydride, being a strong electron acceptor, undergoes oligomerization even in presence of a weak nucleophile like ester enolate.

6.3.4 Reaction between 2,3-dimethylmaleic anhydride and MTS

As expected, in absence of a catalyst no reaction of 2,3-dimethylmaleic anhydride with MTS was observed (entry 1, table 6.4). In the presence of a nucleophilic catalyst TBABB or Lewis acid catalyst $Yb(OTf)_3$, 2,3-dimethylmaleic anhydride reacts with MTS (scheme 6.8) resulting in a 1,2-adduct (entry 2-5, table 6.4). The reaction was found to be clean and quantitative as evidenced by TLC.



(8) **MTS (2)** **(9)**

Scheme 6.8 Reaction between 2,3-dimethylmaleic anhydride and MTS using TBABB catalyst

TBABB (0.1 mol%) was sufficient to catalyze the 1,2 addition reaction between 2,3-dimethylmaleic anhydride and MTS (entry 5, table 6.4). In view of the difficulties experienced with maleic anhydride, we explored the reaction of 2,3-dimethyl maleic anhydride with MTS. We reasoned that the methyl substitution would prevent oligomerization of the anhydride.

The results are summarized in table 6.4. The ^{1}H and ^{13}C NMR spectrum of the product 9 **isolated as the silyloxy derivative is shown in Fig 6.7 and Fig 6.8 respectively (entry 4, table 6.3). The spectra confirm the proposed structure. The DEPT spectrum of** 9 **is shown in Fig 6.9.**

Table 6.3 Reaction between 2, 3-dimethylmaleic anhydride and MTS at 30^{o}C

Entry	MTS, mmol	2,3-Dimehtyl maleic anhydride, mmol	Catalyst	Solvent, mL	Time, h	1,2-silyl adduct (**9**) (Isolated yield) %
1	$1.58x10^{-3}$	$1.58x10^{-3}$	nil	THF, 10	12	No reaction
2	$1.387x10^{-3}$	$1.387x10^{-3}$	$Yb(OTf)_3$ 10 mol%	CH_2Cl_2 10	2	96
3	$7.13x10^{-4}$	$7.13x10^{-4}$	TBABB 0.5 mol%	THF, 10	1	95
4	2.46	2.46	TBABB, 1 mol%	THF, 20	2	98
5	2.46	2.46	TBABB, 0.1 mol%	THF, 20	2	96

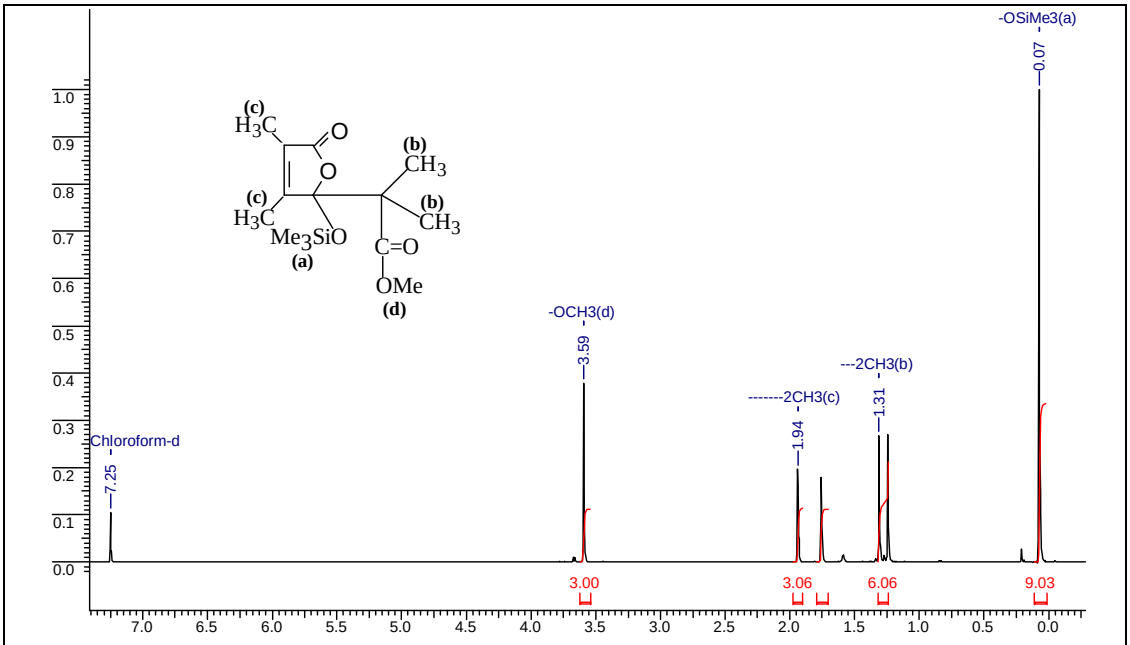


Fig 6.7 ^{1}H NMR spectrum of 1,2-adduct of 2,3-dimethylmaleic anhydride (9) in $CDCl_3$ (500 MHz) (entry 4, table 6.3)

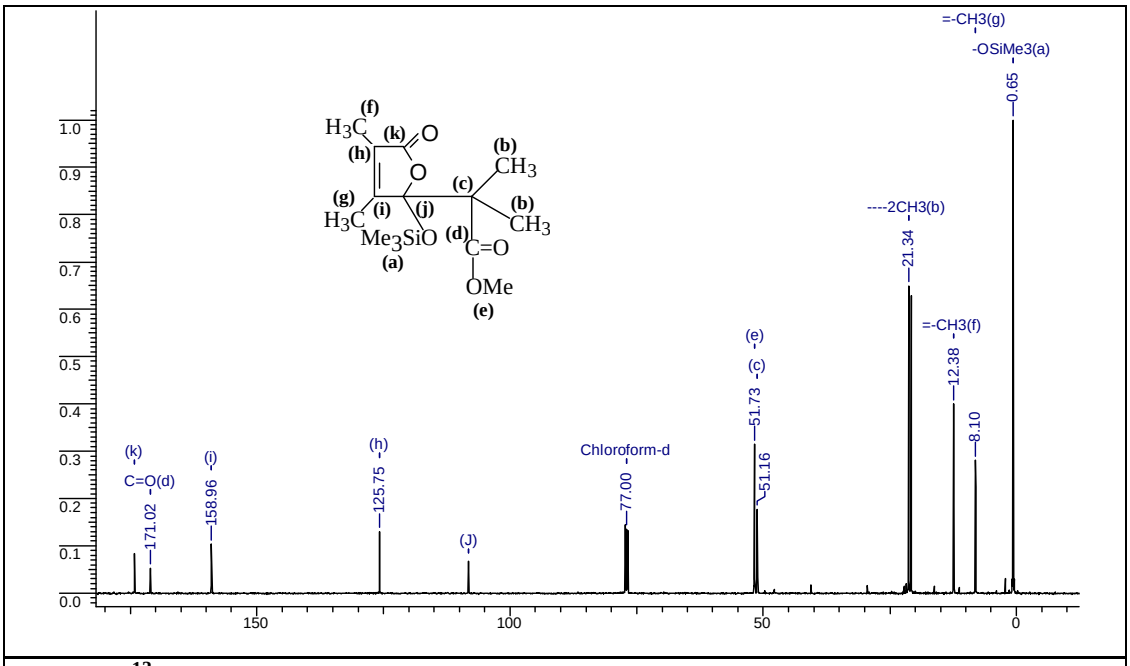


Fig 6.8 ^{13}C NMR spectrum of 1,2-adduct of 2,3-dimethylmaleic anhydride (9) in $CDCl_3$ (125 MHz)(entry 4, table 6.3)

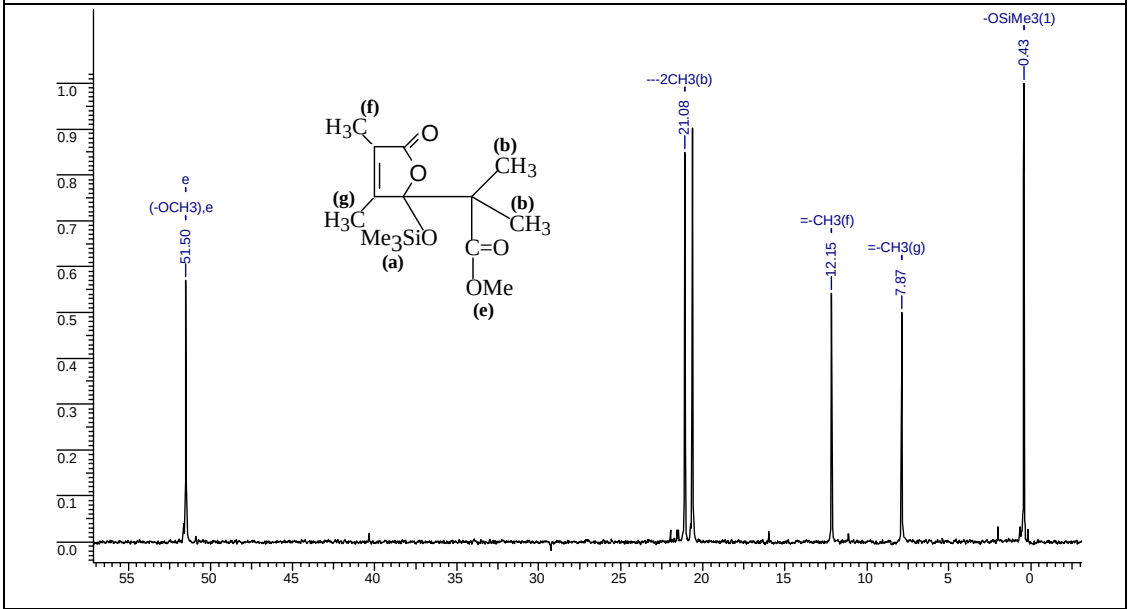


Fig 6.9 DEPT of 1,2-adduct of 2,3-dimethylmaleic anhydride (9) in $CDCl_3$ (500 MHz) (entry 4, table 6.3)

The silyloxy derivative, 9, was desilylated using TBAF/MeOH at 30°C for 1h. The silyl peaks disappeared completely. However, the resulting products exhibited three spots. Column chromatography of the mixture, gave a viscous yellow liquid in 80% yield.

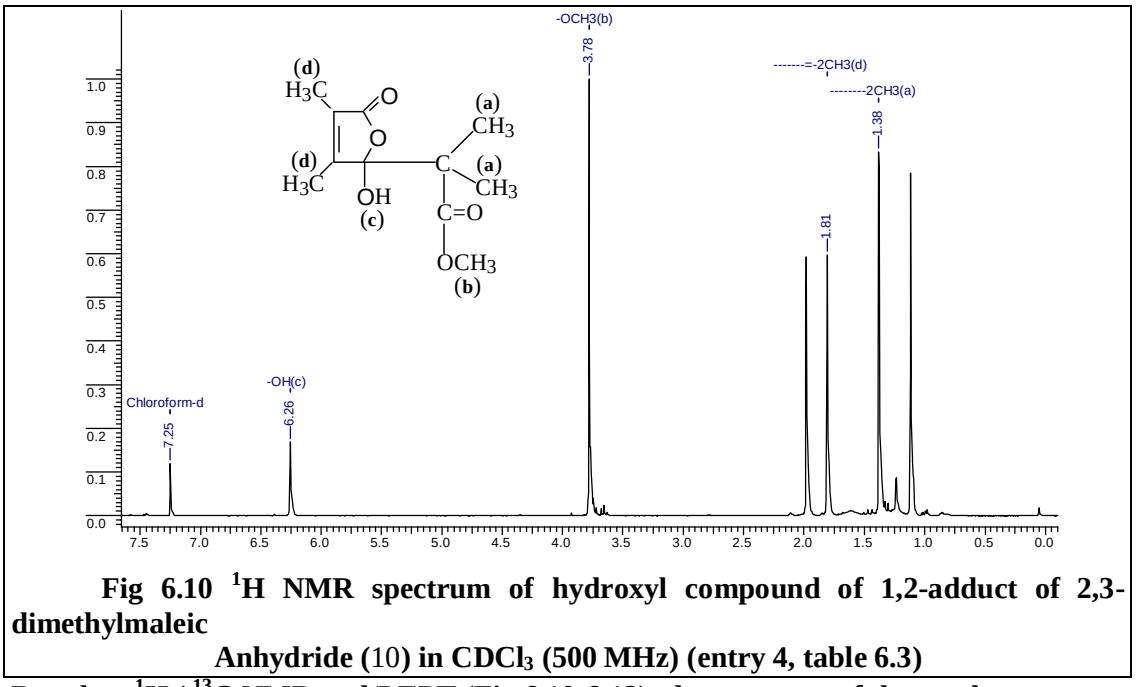
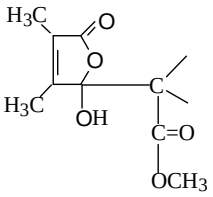


Fig 6.10 ^{1}H NMR spectrum of hydroxyl compound of 1,2-adduct of 2,3-dimethylmaleic

Anhydride (10) in $CDCl_3$ (500 MHz) (entry 4, table 6.3)

Based on ^{1}H / ^{13}C NMR and DEPT (Fig 6.10-6.12), the structure of the product was confirmed as 10.



10

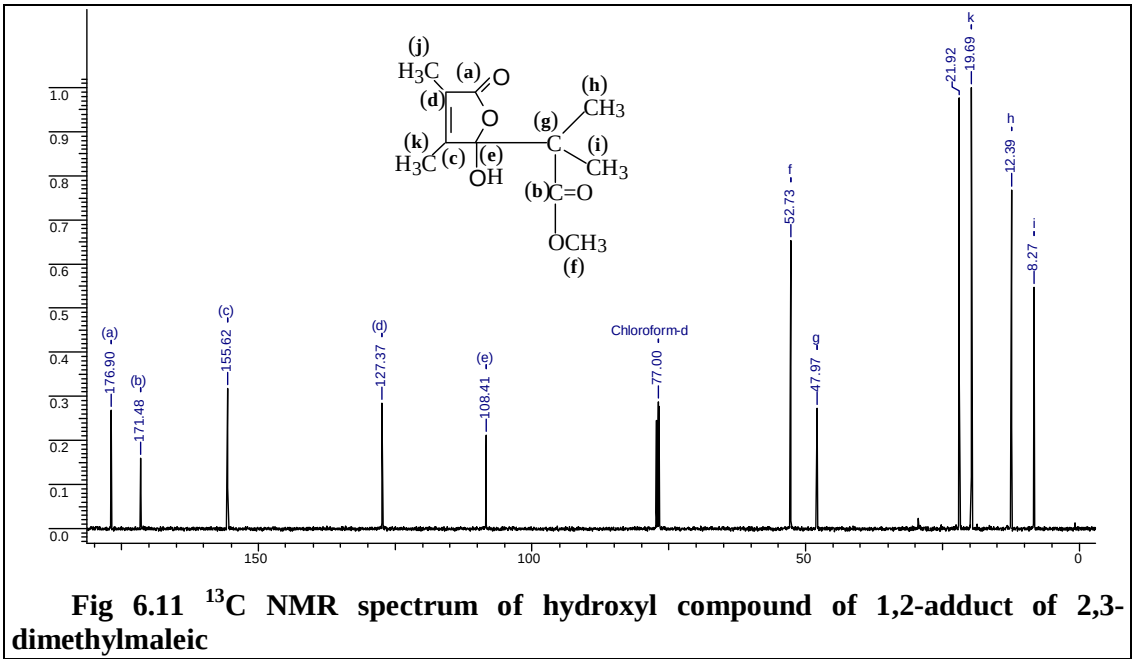


Fig 6.11 ^{13}C NMR spectrum of hydroxyl compound of 1,2-adduct of 2,3-dimethylmaleic

anhydride (10) **in $CDCl_3$ (125 MHz) (entry 4, table 6.3)**

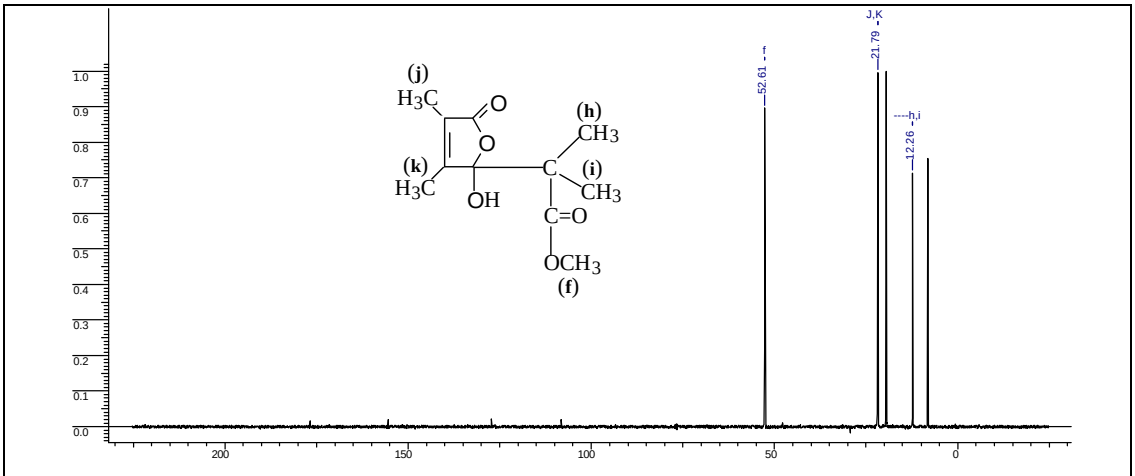
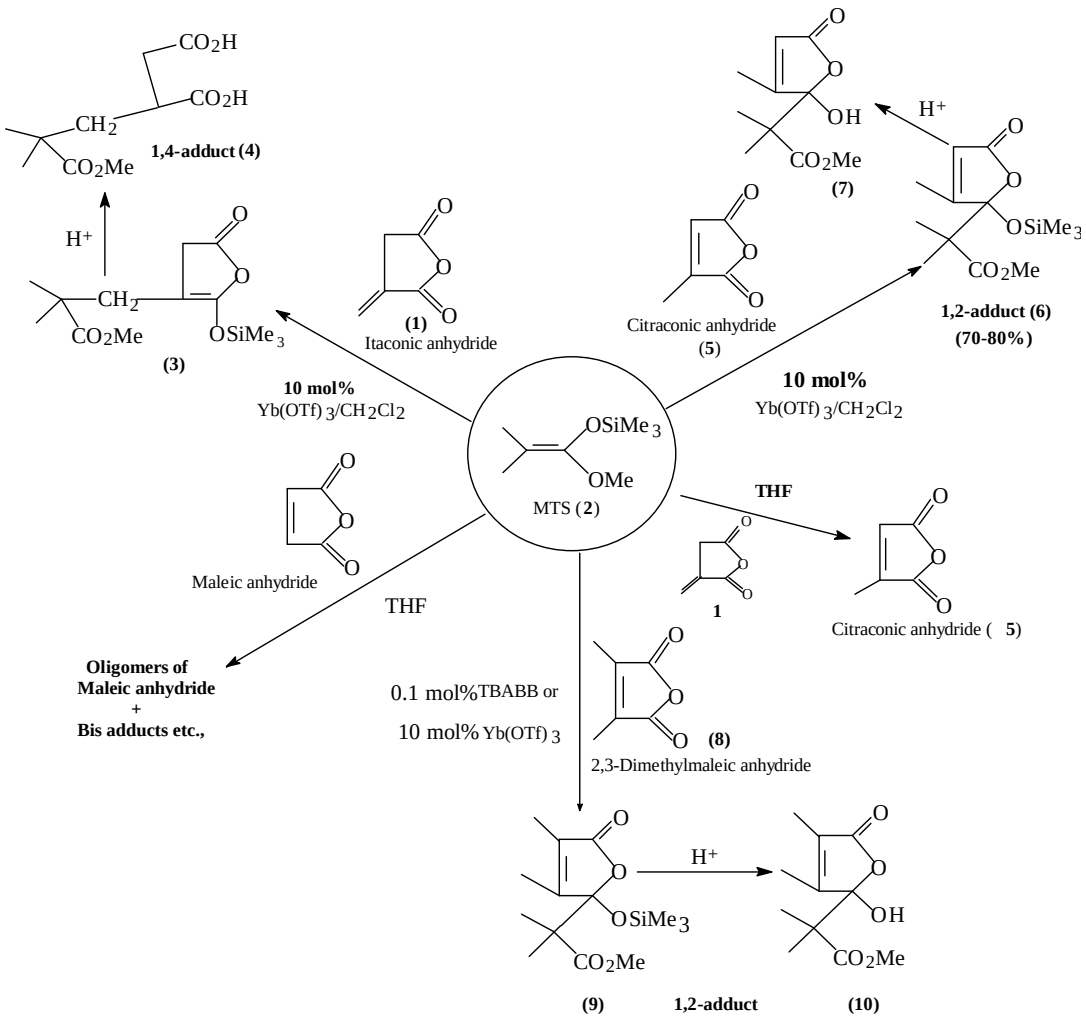


Fig 6.12 DEPT of hydroxyl compound of 1,2-adduct of 2,3-dimethylmaleic anhydride (10)
in $CDCl_3$ (500 MHz) (entry 4, table 6.3)

6.4 Conclusions

Based on the foregoing study, the reactions of MTS with various cyclic anhydrides can be summarized as shown in scheme 6.9. 1,2-addition is the preferred pathway with both 2,3-dimethyl maleic anhydride and citraconic anhydride. Where as itaconic anhydride isomerizes to citraconic anhydride in presence of MTS in THF, in less polar solvents (CH_2Cl_2) and in presence of Lewis acid catalysts ($Yb(OTf)_3$), MTS adds to itaconic anhydride in a 1,4-fashion, resulting in the dicarboxylic acid functionality. However, in none of the cases, we could obtain an anhydride functionality.



Scheme 6.9. Summary of reactions between MTS and various anhydrides

6.5 References

1. Koning, C.; Vanduin, M.; Pagnooulle, C; Jerome, R *Prog. Polym. Sci.* **1998**, 23, 707.

2. Takenaka, K.; Hirao, A.; Nakahama, S. *Macromol. Chem. Phys.* **1995**, 196, 1687.

3. Cernohous, J. J.; Macosko, C.W.; Hoye, T. R. *Macromolecules* **1997**, 30, 5213.

4. Knochel, P. *Synlett* **1995**, 393.

5. Moon, B.; Hoye T. R.; Macosko, C. W *J. Polym. Sci*: *Part A*: *Polymer chemistry*, **2000**, 38,
2177.

6. Malz, H.; Komber, H.; Voigt, D.; Hopfe, I.; Pionteck, J. *Macromol. Chem. Phys.* 1999**, 200,**
642.

7. Argade, N. P. Ph.D. Thesis, 1988**, H. P. T. Arts and R. Y. K. Science College, Nashik,**

Maharashtra, India.

8. (a) Shringer, R. L.; Ford, S. G.; Roll, L. J. ***OSC* 1943,** 2, 140. (b). Galanti, M. C.; Galanti, A.
V. *J. Org. Chem*. **1982**, 47, 1572.

9. Galanti, A. V.; Keen, B. T. *J. Polym. Sci: Poylm. Chem. Ed.* **1981**, 19, 2243.

10.Satoh, K.; Kamigaito, M.; Sawamoto, M. *Macromolecules*, 1999**, 12, 3827.**

11.Forsberg, J. H.; Spaziano, V. T.; Balasubramanian, G. K.; Liu, G. K.; Kinsley, S. A.; **Duckworth, C. A.; Poteruca, J. J.; Brown, P. S.; Miller, J. L. *J. Org. Chem.*** 1987**,**

***52*, 1017.**

CHAPTER 7: SUMMARY AND CONCLUSIONS

7.1. SUMMARY AND CONCLUSIONS

End-functional polymers provide an easy access to block, graft, and star polymers, which have many potential applications as compatibilizers, emulsion stabilizers, moisture retention agents, adhesives, coatings etc. Functional polymers can be synthesized by the use of, either, functional initiators or post polymerization functionalization reactions. The use of functional initiators in living polymerization ensures that each polymer chain contains one functional group. However, initiators of this type are of limited availability and generally require protection of the functional group prior to use. Some functional initiators of GTP gave poly (methyl methacrylate) s with broad molecular weight distribution and less than quantitative conversion of monomer i.e. in a non-living process. Each functionalization/end-capping reaction is unique and requires optimization of the reaction conditions to ensure quantitative functionalization. In GTP, cyclotermination is considered to be major termination process. The disadvantage of termination approach to chain end functionalization is that any polymer chains that are not living will not result in functionalization.

Secondary hydroxyl-terminated poly (methyl methacrylate) s was prepared by group-transfer polymerization with narrow molecular weight distribution (M_w/M_n = 1.06-1.19), initiator efficiencies ($I_{efficiency}$) in the range of 0.78-1.10 and functionalization efficiencies in the range of 0.70-0.80. From MALDI ToF studies of hydroxyl-terminated PMMA, it is observed that cyclized chains are formed along with chain growth, particularly, during or just before functionalization reaction. This strongly supports a dissociative mechanism for GTP in which ester enolates acts as initiator as well as catalyst. It was found that use low TBABB catalyst concentration and slow addition of MMA is desirable from the point of view of keeping the chain end cyclization as low as possible.

Lactone-end capped PMMA was prepared using 0.1-mol% TBABB catalyst in THF at room temperature using 5,6-Dihydro-2H-pyran-2-one, as an electrophile with good initiator efficiency (0.8-1.05) and narrow molecular weight distribution (M_w/M_n = 1.08-1.11). Efficiency of functionalization was in the range of 0.70-0.85. MALDI ToF MS spectra of lactone-end capped PMMA reveals that cyclic fraction can be kept to the minimum using low concentration of TBABB catalyst.

Narrow molecular weight amine-terminated poly (methyl methacrylate) s was prepared by group-transfer polymerization with good initiator efficiency ($I_{efficiency}$) (0.84-1.06), narrow molecular weight distributions (Mw/Mn = 1.07-1.11) and with F_n in the range 0.80-0.85. MALDI ToF mass spectra of amine terminated PMMA shows the presence of competing chain end cyclization reactions along with functionalization. High concentration of Lewis acid catalyst (ZnI_2) and long reaction time may result in increased occurrence of cyclization reaction.

When Lewis acid like $Yb(OTf)_3$ is used in CH_2Cl_2 solvent, a Michael type adduct is formed between itaconic anhydride and MTS at room temperature. However, a strong Lewis acid $Yb(OTf)_3$ cannot be used for functionalization of silyl ketene acetal ended poly (methyl methacrylate) s in THF. Anhydrous $Yb(OTf)_3$ causes ring opening polymerization of THF. Additionally, $Yb(OTf)_3$ can also co-ordinate to C=O group of poly (methyl methacrylate) s. 2,3-Dimethylmaleic anhydride gave 1,2-addition product with MTS using both nucleophilic TBABB/THF as well as Lewis acid $Yb(OTf)_3/CH_2Cl_2$ catalytic system in quantitative yield. Citraconic anhydride gave 1,2-addition as a major product with MTS using Lewis acid $Yb(OTf)_3/CH_2Cl_2$ catalytic system at room temperature. However, no suitable conditions could be found under which a silyl ketene acetal could be added to an anhydride in a 1,4-fashion, which could be compatible with GTP reaction conditions. Hence, attempts to prepare an anhydride end functional PMMA could not succeed.

7.2. Perspectives for future

Work reported in this thesis on the synthesis of end-functional poly (methyl methacrylate) s has opened up many new perspectives for future research. These are as follows:

- Hydroxyl terminated PMMA prepared by GTP can be used in ring-opening polymerization of ε-caprolactone (ε-CL) using $AlMe(BHT)_2$ by coordination insertion mechanism to obtain PMMA-b-poly (ε-CL).

- Hydroxyl terminated PMMA can be used for the synthesis of methacryloyloxy terminated PMMA, which is a useful macromonomer.

- Ring opening polymerization of lactone group in lactone end functionalized PMMA can lead to the synthesis of PMMA-b-poly (lactone) s.

- Amine-terminated PMMA can be used in reactive blending with anhydride-terminated polymers.

LIST OF PUBLICATIONS

1. ***The Mukaiyama-Michael Addition of a β,β-Dimethyl Substituted Silyl Ketene Acetal to α,β-Unsaturated Ketones Using Tetra-n-butylammonium bibenzoate as a Nucleophilic Catalyst.***
   *R. Gnaneshwar**, P. P. Wadgaonkar and S. Sivaram** Tetrahedron Letters 2003, **44, 6047.***

2. Conjugate Addition of a Silyl Ketene Acetal to α, β-Unsaturated Lactones
   R. Gnaneshwar and S. Sivaram **Synthetic Communications 2006,** 36, 885.

3. End-Functional Poly (methyl methacrylate) s via Group Transfer Polymerization
   R. Gnaneshwar and S. Sivaram (to be communicated to **Macromolecular Symposia**)

4. Lactone-End Capped Poly (methyl methacrylate) s via Group Transfer Polymerization
   R. Gnaneshwar and S. Sivaram (to be communicated to **Macromolecular Rapid Communications**)

5. Silyl Ketene Acetals as C-Nucleophiles in the Carbon-Carbon Bond Forming ***Reactions***
   *R. Gnaneshwar **and S. Sivaram (to be communicated to** Synthesis**)***