Mass Spectrometric Analysis of Chain End Functionalization in *ab initio* Cationic Polymerization

*Weihong Lang, Steve Rimmer**

Polymer and Biomaterials Chemistry Laboratories, Department of Chemistry (The Polymer Centre), University of Sheffield, Sheffield, S3 7HF, England

Summary: Matrix assisted laser desorption ionization time of flight mass spectrometry (MALDI-TOF MS) and LC-ESI MS was applied in the analysis of *ab initio* chain end functionalization in cationic polymerization of *iso*butyl vinyl ether. Well-resolved mass spectra of vinyl ether oligomers were obtained. The MALDI spectra give information on polymerization and functionalization process, as well as chain end functionality and side reactions occurred in the system.

Introduction

Mass spectrometry has now become a well-established analytical tool in the armoury of the polymer chemist. Of the various ionization sources available the soft-ionization techniques that use either matrix assisted laser desorpion ionization (MALDI) or electrospray ionization (ESI) are by far the most useful at the current time. MALDI is typically coupled to time of flight analysis (MALDI-TOF) but other detection methods such as ion cyclotrons are sometimes used. ESI on other hand is frequently coupled to the full range of mass analysers and quadropole (ESI-Q), ion trap (ESI-IT) and time of flight (ESI-TOF) instruments are frequently employed in many analytical laboratories. Tanaka et al first reported the laser desorption of intact polymer ions in 1988[1] and it is the observation of these molecular ions derived from individual polymer molecules that gives wide ranging appeal to both the MALDI and ESI techniques. Perhaps the most powerful use of these applications is in the determination of non-repeat unit heterogeneities, such as in the determination of end group structures.

In a previous report we showed how oligo(*iso* butyl vinyl ether)s (O*i*BVE) with specific chain functionality could be prepared by incorporation of silyl enol ethers in the initial

 CCC 1022-1360/00/$ 17.50+.50/0

reaction mixture, a method we named *ab initio* cationic polymerization[2]. Cationic polymerization of *iso*butyl vinyl ether (*i*BVE) has been thoroughly investigated[3] and well-controlled living cationic systems have been established.[4] Multifunctional silyl enol ethers were applied to couple the polymer chain ends together and to form multi-armed block copolymers by the same group from 1993 to 1996.[5, 6] In conventional preparations of end functional oligomers by ionic polymerization, living systems are developed so that the living chain end (anionic or cationic) can then react with a capping agent and this results in the addition of chain-end functionality. However, in the *ab initio* variant the capping agent is added at the start of the reaction and successful functionalization relies on balancing the various rate constants (propagation rate constant, k_p, end-capping rate constant k_{cap} and the rate constants of any side reactions, k_{side}). In the ideal situation $k_p \approx k_{cap} >> k_{side}$. However, measurement of these parameters is far from trivial. Therefore, in order to understand these polymerizations we prefer to produce complete analytical data on the reaction products and then observe changes in these data as the reaction variables are altered. Mass spectrometry is a vital tool and here-in we describe the application of both MALDI-TOF MS and ESI-Q MS to the elucidation of end groups produced during the *ab initio* cationic polymerization of *i*BVE. Prior to this work Katayama has reported on the optimization of MALDI TOF MS for the analysis of O*i*BVE.[7]

Results and discussion

Analysis of O*i*BVE prepared in absence of silyl enol ethers

O*i*BVE were prepared by using *i*BVE:HCl as an initiator, $SnCl_4$ as co-initiator and methanol was added after polymerization had ceased in order to cap any living chains with the methoxide group. Polymerizations were conducted between –78 and 21°C. A MALDI-TOF mass spectrum of a product derived from polymerization at -78°C in the presence of tetrabutylammonium chloride, terminated with methanol after 5 minutes reaction time is shown in figure 1. It is composed predominantly of one series of mass peaks that are separated by the repeat mass of the *i*BVE repeat unit (100 g mol.$^{-1}$). Each peak mass can be accounted for by the structure shown in the insert, i.e. the oligomers possess α-H, ω-methoxy end groups and cationization is mainly due to addition of a single sodium ion except were otherwise indicated. The addition of methanol was used to

cap any living chains still active after propagation. These data clearly indicate that at -78°C this polymerization is a living or pseudo-living system. However, small peaks at m/z = 100n + 68 are observed and are due to aldehyde end groups produced by water capping or the process shown in scheme 1. The other peak serials at m/z = 100n + 85 is not easily assigned the best possible assignment is the aldehyde chain end with potassium ionization. Also small amounts of the di*iso*butanol chain end were detected on this spectrum.

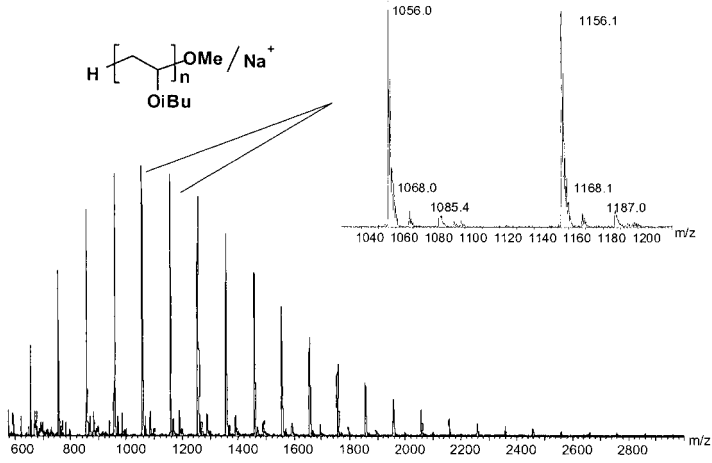


Figure 1: MALDI-TOF spectrum of *OiIBVE* sample prepared at low temperature (-78°C /*n*-Bu_4NCl/5min)

In agreement with Katayama et al's report we observed that as the polymerization temperature was increased the polymerization became less living, that is end groups that were derived from events other than capping of the carbocationic chain end with methanol became significant. An expansion of a typical spectrum derived from O*i*BVE prepared at 0°C in the absence of *n*Bu_4NCl is presented in figure 2.

In the mass spectra derived from these higher temperature polymerizations, it was possible to identify nine separate serials of mass peaks and the structures that can feasibly give rise to these peaks are identified on figure 2. Reactions that lead to these structures are displayed in schemes 1, 2 and 3.

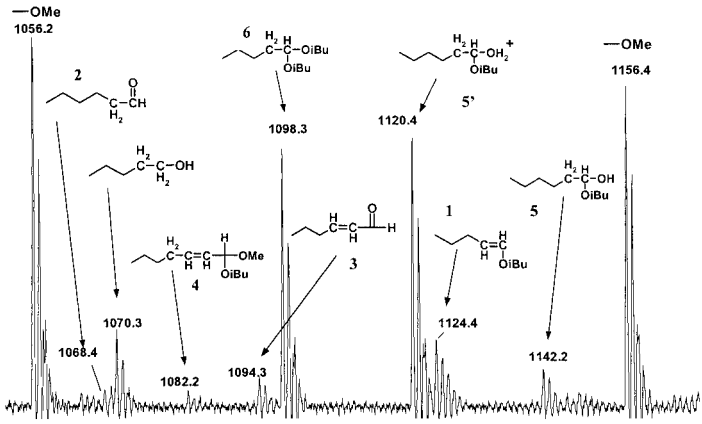
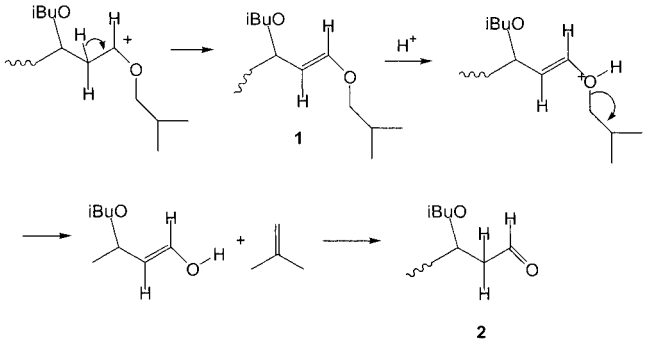


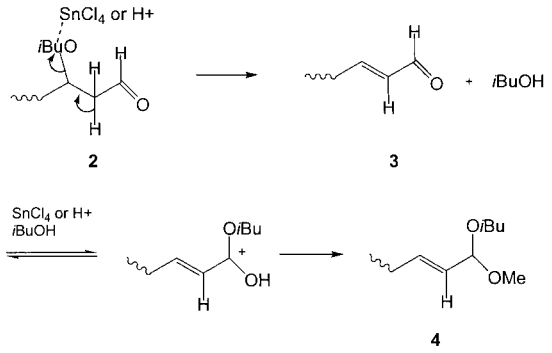
Figure 2: Side reactions observed by MALDI at higher polymerization temperature (0°C /60min)



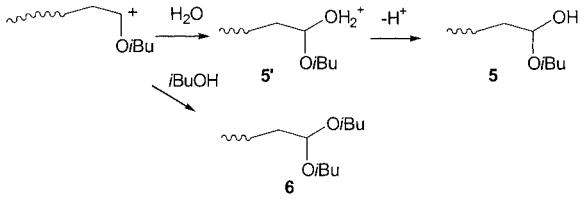
Scheme 1: Formation of alkene and aldehyde chain end

One of the significant side reactions is elimination of the β-proton to give compound **1** as shown in scheme 1. Production of **1** leads via the mechanisms shown in scheme 1 and 2 to isobutanol, **2, 3** and **4**. Scheme 3 shows how the addition of adventitious water or *iso*butanol, produced following scheme **2**, leads to compounds **5', 5** and **6**. Katayama[8] et

al. recently proposed that **2** can be produced by elimination of isobutanol from **5**. However, **2** can also be produced by elimination of 2-methylpropene from **1**, as shown in scheme 1, and experiments are currently underway to investigate this alternative pathway.



Scheme 2: Formation of internal alkene aldehyde and internal alkene methoxy chain ends



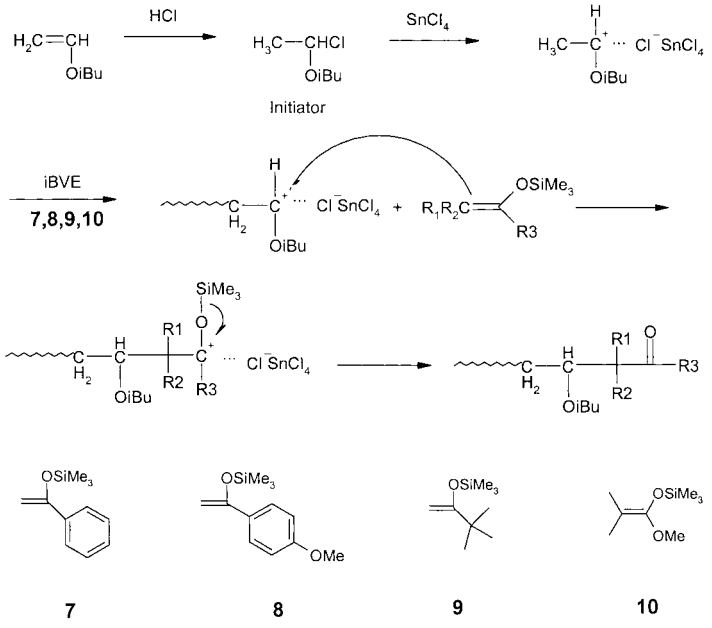
Scheme 3: Formation of hydroxyl and diisobutanol chain ends

β-proton elimination has a higher activation energy than the monomer propagation reaction[9] and therefore it is not surprising that the alkene chain end, **1**, is absent for the O*i*BVE prepared at the lowest temperature, -78°C in the presence of nBu$_4$NCl (Figure 1). The suggested chain end structure is also listed on figure 2 for another significent peak, m/z = 100n + 70. The peaks may arise from α-H, ω-ethylhydroxy but a chemical rationale to this groups is not yet available. The peaks due to methoxy chain ends,

derived from capping of living polymer chains with methanol, were observed, following polymerization at 21°C, but they were vanishingly small so that the polymerization was essentially non-living at this temperature.

MALDI-TOF MS analysis of O*i*BVE prepared by *ab initio* cationic polymerization

In our previous report we showed that in the non-living polymerization of *i*BVE, catalyzed by $Yb(OTf)_3$ addition of silyl enol ethers at the start of the polymerization produces oligomers with ketone chain end functionality[2]. In this work we extended these polymerization to include the silyl enol ether **10**, as shown in Scheme 4, and employed a better-defined system based on the use of $SnCl_4$ as co-initiator.



Scheme 4: *In situ* end-capping in cationic polymerization of *i*BVE

Figure 3 shows expansions of MALDI-TOF mass spectra of O*i*BVE obtained from parallel polymerizations at -78°C in the absence and presence of the silyl enol ethers **7, 8, 9** or **10**. As noted previously the polymer chains were ionized by the attachment of a

single sodium ion. A distribution of chain ends still formed at this low temperature in the absence of additive or silyl enol ethers but all are reduced or totally disappeared when silyl enol ethers were added to the polymerization.

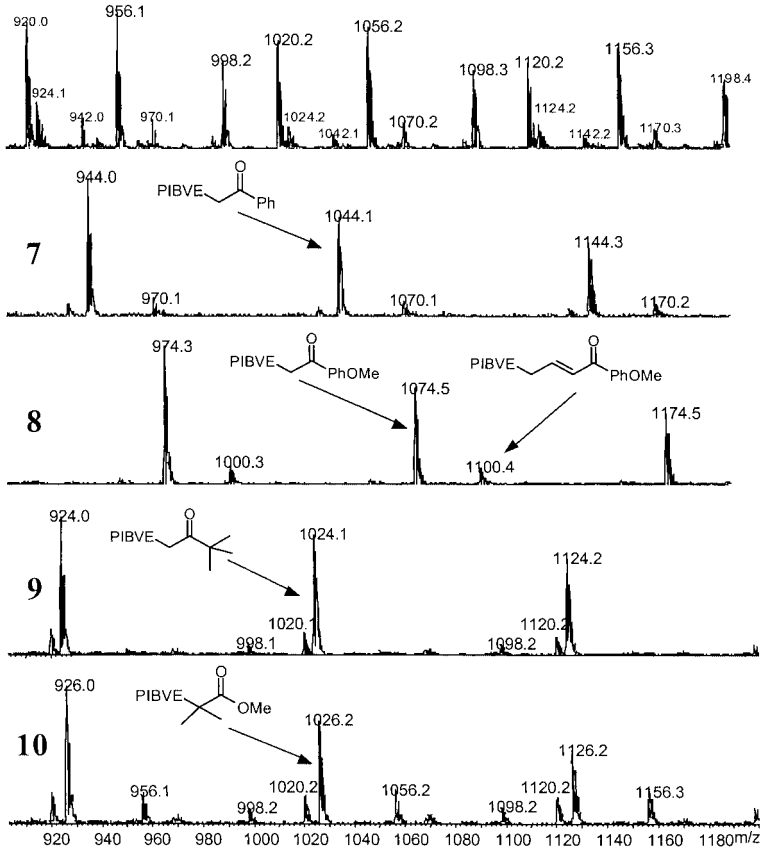


Figure 3: MALDI-TOF of *OiBVE* functionalized by end-capping agents (-78°C/60min)

Each of these polymerizations involved attempted chain quenching by methanol at the end of the reaction but the absence of mass peaks associated with methoxy chain ends indicated that living chain ends were absent at the time of quenching over this molecular weight range when **7** or **8** were used. Significantly the mass peaks associated with

transfer and termination reactions that lead to the end groups **1** – **6** were absent from these two spectra.

However, the spectra indicated that the methoxy chain end was formed at higher chain length when the most reactive silyl enol ether, **8,** was applied, even at lower polymerization temperature. This could be due to the high reaction rate of end capping of **8** compared with chain propagation. After **8** was consumed, monomer continued to propagate and formed longer O*i*BVE chain and eventually was terminated by methanol. molecular weight effect was not apparent when **7**, **9** or **10** were applied. The alkylation of carbocations by silyl enol ethers is known to produce ketone functionality, as shown for a the reaction of a macrocarbocation in scheme 4, when silyl enol ethers are used as capping agents in living cationic polymerizations[5, 6].

It can be seen from Figure 3 that the relatively less reactive silyl enol ethers **9** and **10** also produce high chain end functionality and lead to reduced frequency of side reactions. Therefore, the data show that in all of these cases the rate of alkylation with the silyl enol ethers **7** – **9** is faster than most of the side reactions that were observed in the polymerization described in the previous section. However, the rate of alkylation must be slower than propagation since, clearly propagation still progresses. Elimination reactions produce aldehyde chain ends, which if they are produced can also react with silyl enol ethers to produce chain end functionality and this reaction is an important feature of the polymerizations since it ensures that the product maintains a high degree of functionality. In each case a small fraction of the chains was found to be functionalized in this way and the mass peaks associated with these aldol products (α,β-unsaturated ketone after dehydration of β-hydroxy ketone) from the capping by **8** is shown in figure 3.

Mass discrimination and quantification of the MALDI TOF mass spectra

Complementary information was obtained by ESI MS analysis of the O*i*BVE. Figure 4 compares the ESI mass spectrum and the MALDI-TOF mass spectrum of the same O*i*BVE functionalized by **7**. The ESI mass spectrum confirmed the high chain end functionality of the oligomer sample. Both MALDI and ESI show that the dominant

chain end arises due to alkylation of **7** by the propagating chain end and the repeat unit of m/z = 100, for O*i*BVE , is clearly seen. In both spectra these is little evidence for methoxy chain ends. However, it can be seen that the MALDI process was subject to under-presentation of oligomer chains with higher molecular weight so that the distribution of oligomer adducts were shifted to the lower molecular weight. According to the MALDI-TOF mass spectrum, the oligomer chain with 4 repeat units (m/z = 543.5) had the highest intensity and this indicates that many very short functionalized polymer chains were formed. On the other hand the ESI result showed that the same oligomer chain (m/z = 544.2) was less than 10% of the intensity of oligomer chain with 9 repeat units. The polymer ion distribution of ESI is more reliable than MALDI due to the different sample introduction procedure. ESI avoids the difficulties that non-homogeneous sample preparation, and uneven polymer ion desorption that MALDI can introduce. However, multiple charging was sometimes observed in the ESI analysis, although this was not seen in the sample shown in figure 4. The relative intensities of the various mass peaks derived from the ESI process were similar to those derived from MALDI-TOF MS. Therefore, it is reasonable to assume that the different chain end structures do not seriously affect sodium ionization to O*i*BVE and that the ionization site does not mainly lie on chain end.

The ESI result indicated that not many polymer chains with repeat numbers less than 7 were formed during in-situ end capping. This is an important observation since very low molecular weight oligomers could cause problems in some applications, for example if they were to leach from the final material. The above experiments indicate that the MALDI process can not be used to produce accurate molecular weight distributions. However, a measure of chain functionality could be obtained by comparing mass peaks within a single mass envelope of constant repeat number, obtained over a narrow range of m/z. NMR can also be used to obtain such data and Figure 5 compares the chain end functionality data from both MALDI and the integration of proton NMR spectra.

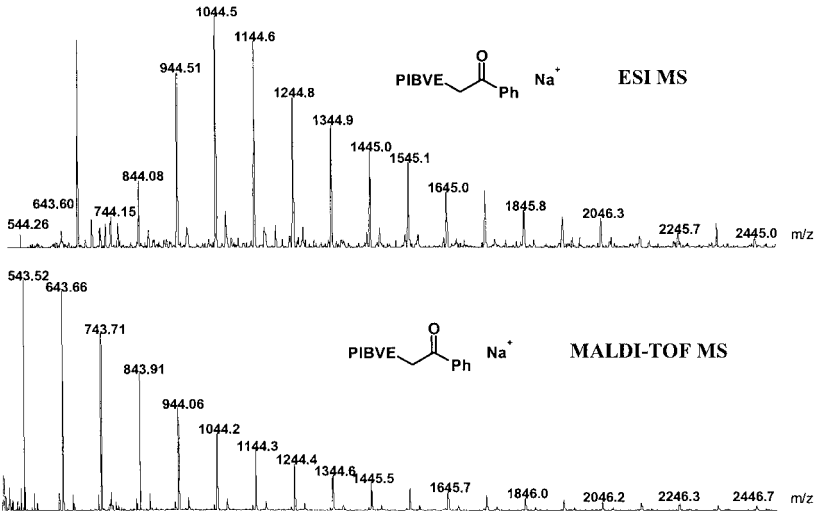


Figure 4: Compare of ESI MS and MALDI-TOF MS on O*i*BVE sample(-78°C/60min)

The points give the chain end functionalities obtained from subtracted MALDI spectra by comparing different chain end intensities within one repeat. The filled points show data from O*i*BVE sample polymerized at -78°C, while for the open squares give the chain end functionalities of O*i*BVE polymerized at -15°C. NMR analysis gave the average chain end functionality, for O*i*BVE prepared at -15 and -78°C sample, as 46% and 86% respectively.

The NMR method for determining the fraction of chains with the desired functionality is also associated with errors. For example, the small fraction of chains initiated by protons could not be accurately determined because the resonance from the chain end proton was overlapped with the methyl proton-resonances from the *iso*butyl group. Also the precision in chain end functionality values depend on signal to noise ratio, which can be low when attempting to integrate end groups at low concentration.

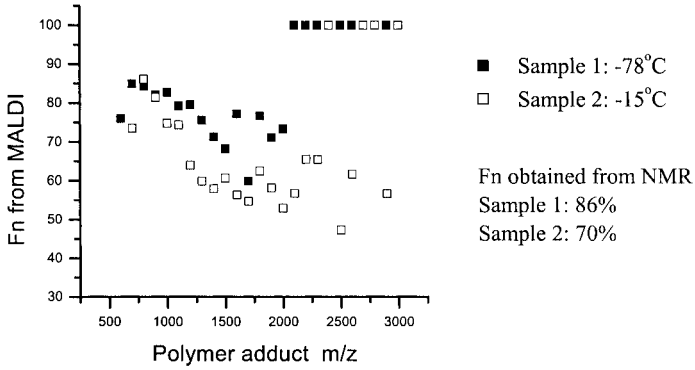


Figure 5: Comparison of chain end functionality from MALDI and NMR

As mentioned previously, the MALDI process suffers from problems associated with heterogeneous sample preparation, polymer ion desorption and possibly uneven ionization. However the data in figure 5 essentially agree the with average functionalities obtained from the NMR spectra of the two samples and comparison over the small mass ranges used when comparing oligomers of constant repeat number appears to be a valid procedure.

Experimental Part

Polymerization of IBVE

Polymerization of *i*BVE were carried out at 21°C, 0°C, -15°C, and -78°C under dry nitrogen in a cooling bath carousel. The polymerizations were initiated by the addition of a solution of $SnCl_4$ or $SnCl_4$ with n-Bu_4NCl (pre-chilled when the polymerization temperature was -78°C) to the cold solution containing *i*BVE, initiator and silyl enol ether. The polymerizations were carried out from 5 minutes upto 1 hour and was terminated by the addition of a solution of ammonia in methanol. The product polymer solution was washed with HCl_{aq} (1 mol. dm^{-3}) twice and 1M $NaOH_{aq}$ (1 mol. dm^{-3}) twice and then distilled water twice. The solvent was removed to give the product oligomer.

NMR

^{1}H NMR spectra were obtained on a Bruker AC250 or a AMX2-400 spectrometer using deuterated chloroform at room temperature. Chloroform was used as internal standard.

MALDI-TOF MS

MALDI-TOF mass spectra were obtained using a TofSpec-2E instrument, Micromass, equipped with co-axial geometry with single stage reflectron with a 1.5m flight tube. The 337-nm nitrogen UV laser had a pulse width of 4ns and each pulse had an energy of 180 microjoules. Experiments were carried out in reflectron mode at accelerating potential of 20kV. External calibration was applied to each sample plate. The polymer samples were dissolved in THF (30mg cm^{-3}). DHB (25mg cm^{-3} in THF) was found to be the optimum matrix and sodium iodide (3 mg cm^{-3} in THF) was used as the cationization agent. 10μl of the polymer solution, 10 μl of matrix solution and 10 μl of NaI solution were mixed together prior to spotting on the target plate. 2 μl of this solution was applied to the target plate. The target plate was allowed to dry fully before being loaded into the MALDI-TOF MS instrument

.

Standard solution preparation

Each standard peptide was dissolved (1mg cm^{-3}) in TFA_{aq} (0.1% v/v), stored in sealed amber sample tubes at 0°C and thawed as required. Matrix solution was prepared by dissolving 10 mg of sinapinic acid in 1 ml of water/acetonitrile/TFA (60:40:0.1 pbw respectively). Due to the variable quality of this matrix the sinapinic acid was recrystallised from a MeOH/Pentane mixture.

ESI-MS analysis

ESI-MS analysis was carried out using a Micromass LCZ Platform instrument operating in ESI mode with a 4000 Dalton mass range single quadrupole mass analyzer. The optimized parameters were set at: Capillary voltage 3.5 kV, Cone voltage 130V, Extractor voltage 4 V, Desolvation temperature 300°C.

Acknowledgment

The authors would like to express thanks to Dr. Peter Turner and Dr. Zuifang Liu for their assistance in performing the mass spectrometry experiments, Lancaster University/University of Sheffield/CVCP for providing a research studentship for W.Lang.

References

1. K.Tanaka, H.Waki., Y. Ido, S. Akita, Y. Yoshida, T. Yoshida, *Rapid Commun. Mass Spectrom.*, 1988. 2: p. 151.
2. W. Lang, S. Rimmer, *Macromolecular Rapid Communications*, 2001. 22(3): p. 194-198.
3. T. Higashimur, M. Mitsuhashi, and M. Sawamoto *Macromolecules*. 1979. p. 178-82.
4. M. Miyamoto, M. Sawamoto, and T. Higashimura, *Macromolecules*. 1984. p. 265-8.
5. H. Fukui, M. Sawamoto, and T. Higashimura, *Macromolecules*. 1993. p. 7315-21.
6. H. Fukui, et al., *Macromolecules*. 1996. p. 1862-6.
7. H. Katayama, H. Kitaguchi, M. Kamigaito, M. Sawamoto, *J. Polym. Sci., Part A: Polym. Chem.* 2000. p. 4023-4031.
8. H. Katayama, M. Kamigaito, M. Sawamoto, *Journal of Polymer Science: Part A: Polymer Chemistry*, 2001. 39: p. 1249-1257.
9. K. Matyjaszewski, *Macromol. Symp.* 1996. p. 53-63.