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Analysis of Hydrocarbon Polymers by Matrix-Assisted Laser Desorption/Ionization–Fourier Transform Mass Spectrometry

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A quick and effective sample preparation is demonstrated for matrix-assisted laser desorption/ionization (MALDI) analysis of nonpolar polymers. Polyisoprene, polystyrene, and polybutadiene polymers were investigated by using as matrix a 2,5-dihydroxybenzoic acid and silver nitrate combination. Silver cationized oligomers produce useful spectra that can be signal averaged to characterize polymer distributions extending up to 6000 u by using a 3-T Fourier transform mass spectrometer. Because an electrostatic ion deceleration protocol was used to extend the mass range, trapping discrimination is shown to exist for molecular weight distributions broader than about 2500 u. However, an integral procedure can be used to reconstruct the true polymer profiles through co-addition of signal transients obtained by using various gated deceleration times. For polymers with narrower mass distributions, silver cationization along with signal averaging provides rapid and accurate polymer characterization for nonpolar polymer systems by using standard MALDI Fourier transform mass spectrometry instrumentation. © 1997 American Society for Mass Spectrometry (*J Am Soc Mass Spectrom* 1997, 8, 225–233)

Determination of a polymer's molecular weight distribution is vital to correlating and understanding properties of a particular polymer system. Rapid analysis can provide feedback and a means of studying polymer kinetics and synthesis strategies. It is therefore highly desirable to have a rapid and accurate analytical technique such as mass spectrometry. Mass spectrometry provides absolute molecular masses, as opposed to relative values such as those obtained from gel permeation chromatography (GPC), laser light scattering, and osmometry, which depend upon a property of the polymer. In addition, it can give information on the repeat unit(s), end groups, additives, impurities, and side products.

Matrix-assisted laser desorption/ionization (MALDI) is a relatively new soft ionization process that produces intact molecular ions, allowing mass spectrometry of higher mass species than was previously possible. By using a variety of matrices, spectra have been obtained for polymers with masses in excess of several hundred thousand units [1–4]. In this context, high resolution Fourier transform mass spectrometry (FTMS) is of interest because it allows manipulation of ions for their selection, dissociation, or reaction with other species in the gas phase. With unparalleled

high resolving power, FTMS is especially well suited for analysis of mixtures such as polymers. It has already been shown that individual oligomers can be mass selected for further study by using the technique of quadrupolar axialization [5]. It may also be possible to accomplish structural analysis of complex polymer systems by use of ion dissociation techniques such as surface-induced dissociation and collision-induced dissociation.

Results presented here describe how to obtain spectra of nonpolar polymers by using standard MALDI-FTMS. In the past, this has been difficult for two reasons. First, nonpolar polymers are a class that is extremely difficult to analyze by mass spectrometry, primarily because of their chemical inertness. This situation has been improved greatly through use of chemical ionization agents such as silver, which can readily attach to nonpolar polymers, causing ionization [6–10]. A second problem is the difficulty of efficiently trapping ions over broad mass distributions. Current upper mass limits are set by the ability to effectively capture ions that are produced during the ionization event. Here, gated trapping is used to slow highly energetic species, allowing for more efficient trapping within the analysis cell. This permits observation of singly charged polymer distributions up to 6000 u in a 3-T Fourier transform mass spectrometer, presented here, and up to 15 ku in a 7-T system [11]. This article demonstrates a facile sample preparation procedure

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and addresses the trapping discrimination encountered from the use of a cubic cell design as it pertains to the analysis of hydrocarbon polymers in a 3-T FTMS system. Signal averaging improves signal intensities and averages out any anomalies from shot-to-shot irreproducibility imparted by the MALDI process. Although not addressed here, the question remains as to whether there is MALDI discrimination for the polymers examined. Ongoing efforts by many groups are testing the accuracy of mass spectrometry employing MALDI ionization [12-16]. Recently, GPC fractionation was combined with off-line time-of-flight mass spectrometry, allowing calibration of the GPC curves against absolute molecular weights [17,18]. It is hoped that these direct comparisons and related studies will definitively show both the accuracy of mass spectrometry and its utility for polymer analysis.

Experimental

Instrumentation

All polymer analysis experiments were carried out by using a 3-T dual cell Fourier transform mass spectrometer (Finnigan FT/MS, Madison, WI). A nitrogen laser (PTI Canada Inc., London, Ontario) having a 600-ps pulse width and operating at 337.1 nm was used for MALDI analyses. The laser beam was directed by two mounted mirrors and focused by both an external lens (fused silica, $f = 1000$ mm; Oriel Corp., Stratford, CT) and internal lens (fused silica, $f = 100.0$ mm; CVI Laser Corp., Albuquerque, NM) to produce spot sizes on the order of 125×250 μm after passing through a 6-in. vacuum viewport flange (Duniway Stockroom Corp., Mountain View, CA) and the 2-mm aperture of a solid conductance limit plate. Although it could be attenuated, the beam size was found not to affect significantly the overall ion abundances or fragmentation of the polymers. The maximum available energy was 1.4 mJ/pulse, which was measured at the laser beam output and corresponded to a power density of 10^9 W/cm². The experimental setup is diagrammed in Figure 1.

Samples were placed on removable stainless steel probe tips measuring 16.5 mm in diameter and

threaded so that they could be properly mounted to the removable sample probe. The probe could then be inserted manually into the chamber following rough pumping of the sample lock region. The source region is pumped by a 700-L/s Edwards diffusion pump (Diffstak model 160, Crawley, West Sussex, England). The analyzer cell uses a smaller Edwards diffusion pump (Diffstak model 100, Crawley), which is rated at 300 L/s. The combination of pumps provides an overall chamber pressure of 2×10^{-8} torr. All experiments were done in the source cell of the 2-in. cubic dual cell to minimize possible mass discrimination from ion transfer past the 2-mm aperture in the solid conductance limit plate separating source and analyzer cells during ion injection. Ions were generated and trapped within 200 μs following the laser pulse. The probe tip was situated approximately 1.0 cm outside of the source trap plate.

Experimental control and data analysis employed a Sun data station (Sparc IPX model 4/50) running Odyssey program software version 3.1 (Finnigan). Stored waveform inverse Fourier transform (SWIFT) excitation functions were generated by the SWIFT cell controller electronics and applied directly to the excitation plates [19,20]. For the narrow molecular weight distribution polymers, a peak (height) search was done following Hamming apodization, and the molecular weight distributions were calculated by using Visual Data Analysis software (Visual Numerics, Houston, TX) and mass corrected for silver attachment. However, spectra were not replotted to show this mass correction. Polydispersities calculated in this way are slightly lower than theoretical expectations, possibly as a result of the use of peak height instead of peak areas.

For the polybutadiene 5000 spectrum, a fixed pressure 2.0-s argon pulse was applied by use of a combination electropneumatic valve (model AV-037-M-P, MDC, Hayward, CA) and a Varian leak valve (model 951-5106, Lexington, MA). The tandem arrangement was operated from an Odyssey pulse valve trigger. A constant pressure of 5×10^{-6} torr could be maintained for any desired length of time to facilitate ion cooling. The inert cooling gas was pulsed to promote ion cooling during the initial ion trapping event to improve signal intensities because the trapping limit of

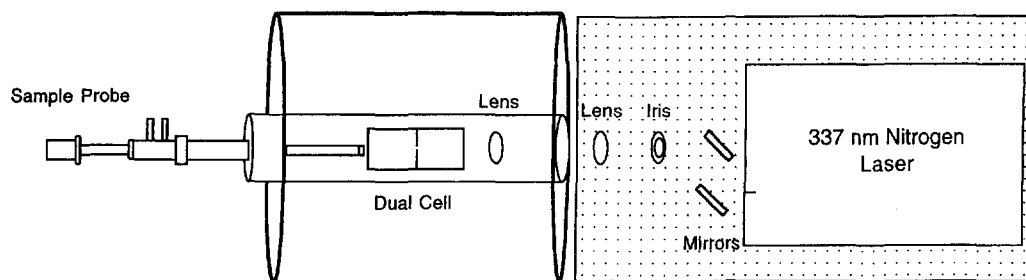


Figure 1. Block diagram for 3-T Fourier transform mass spectrometer showing nitrogen laser setup for MALDI analysis.

the instrument (combination of 3-T field with trapping protocol) was otherwise being reached during polymer analysis.

Sample Preparation

2,5-Dihydroxybenzoic acid (DHB, Fluka Chemical Co., Buchs, Switzerland), a matrix substance, was found to be far superior to *t*-3-indoleacrylic acid [2,16,21] and [2-(4-hydroxyphenylazo)-benzoic acid] [15,22,23] for sample preparation and was used for all MALDI analyses. These three matrices were among those most frequently used by investigators employing other mass spectrometric methods, such as MALDI time-of-flight (TOF) mass spectrometry, for nonpolar polymer analysis. Polyisoprene 650, 1000, and 3000 polymer standards were obtained from Polysciences Inc. (Warrington, PA). Polyisoprene 2700 was obtained from Scientific Polymer Products Inc. (Ontario, NY). Polystyrene 2450 was obtained from Polymer Laboratories Inc. (Amherst, MA). Hydroxyl-terminated polybutadiene 1350 and polybutadiene 2800 were obtained from Polysciences Inc. (see Table 1 for manufacturer's gel permeation chromatography data for the samples where it is available). Polybutadiene 5000 was obtained from Aldrich Chemical Co. (Milwaukee, WI). Samples were prepared by dissolving 10 mg of polymer with a 1:600 to 1:1000 molar ratio (analyte:matrix) of DHB (based upon nominal polymer molecular weight) and adding 10 mL of tetrahydrofuran. Samples were sonicated to facilitate the dissolution process. From this stock solution, smaller aliquots of 1 mL could be taken for analysis at least up to one week following preparation. Prior to analysis, 50 mg of silver nitrate (Aldrich) was added to the 1-mL sample aliquot to form a saturated solution to promote silver cationization. The sample was then applied to the probe tip by using a homebuilt spray apparatus as described previously [24]. The aerospray produces highly homogeneous sample surfaces and uniform crystals. Approximately 200 μ L of sample solution was deposited on the probe tip allowing for between 30 and 50 shots per spot before the surface was depleted and a new sample position was sought by rotating the probe tip. Poly(ethylene glycol)

1000 (Sigma Chemical Co., St. Louis, MO) was used as an external calibrant.

Fourier Transform Mass Spectrometry Parameters

A typical polymer mass spectral measurement consisted of generating silver cationized MALDI ions and trapping them within the cubic cell by applying a 9.5-V decelerating potential to the conductance limit plate, with the source trapping plate grounded, and delaying between 50 and 200 μ s to allow ions to enter the cell before applying static trapping voltages. Following electrostatic ion deceleration and trapping, a delay of up to 5 s was imposed to allow ion relaxation within the cell. Chirp excitations from 50 Hz to 500 kHz at 1100 Hz/ μ s were applied for positive sweeps, and chirp excitations from 500 kHz to 50 Hz at -1300 Hz/ μ s were applied for negative sweeps. For polystyrene 2450 and polyisoprene 3000 samples, SWIFT waveforms generated for the 1500-4500-u mass range were also used and were set to excite ions up to a maximum radius of 1.7 cm. The detection bandwidth was 1 MHz for all experiments and included up to 64K data points. Because the focus of this article is characterization of polymer distributions, high resolution spectra are shown only for polyisoprene 650, which yielded between 2000 and 3000 resolving power for the entire distribution. All other spectra were acquired with low resolution (on the order of 200-300). This was sufficient to see individual oligomers and facilitated calculation of polymer distributions, because all isotopic variants of molecular ions would be contained within the peaks for each oligomer species. In other experiments, unit mass resolution was achievable up to m/z 3000 with concurrent reduction in signal-to-noise ratio (S/N) due to the lowered trapping potentials and consequent loss of ions. Because the ionization efficiency of nonpolar polymers is low, signal averaging was implemented to improve signal levels and also to average out any anomalies from shot-to-shot irreproducibility imparted by the MALDI process. Although a mass spectrum can be obtained from a single laser shot, up to 81 scans were averaged, targeting a theoretical ninefold improvement in S/N. Trap-

Table 1. Comparison of mass spectral molecular weight averages with manufacturer's gel permeation chromatography values

Polymer	Figure	Mass spectrometry results			Manufacturer's GPC results			
		M_n	M_w	Φ	M_n	M_w	M_p	Φ
Polyisoprene 300	2	2854	2919	1.02	—	—	3280	1.05
Polyisoprene 650	4	903	935	1.04	560	650	650	1.16
Polybutadiene, hydroxyl	6	2394	2567	1.07	—	—	—	—
Polyisoprene 1000	8	1272 ^a	1288 ^a	1.01	—	—	—	—
Polyisoprene 2700	9	2733 ^a	2791 ^a	1.02	2460	2660	2610	1.08
Polystyrene 2450	10	2801 ^a	2857 ^a	1.02	2318	2414	2448	1.05
Polybutadiene 2800	11	2927 ^a	2964 ^a	1.01	2760	—	—	1.08

^a Mass-corrected for Ag.

ping voltages were kept at 0.75 V for all experiments except for the polystyrene 2450 sample and polybutadiene 5000 samples, where 2.0-V trapping was employed.

Results and Discussion

Mass Discrimination Effects

Although gated trapping functions by slowing ions as they approach the rear trapping plate, it is not expected that all ions of interest will be trapped properly before the experimental sequence proceeds. In fact, the timing dependence of trapping has been used successfully to discriminate against matrix ions during MALDI measurements [25]. It was previously shown by Dey et al. [26] that polymer distributions from a series of polyethylene glycols could be co-added at different timed intervals following ion formation to reconstruct an accurate distribution. Specific choice of timing delays is a function of both laser wavelength and magnetic field. Thus, the 10- μ s gated trapping time increments suggested by Dey et al. for 7-T measurements may not be appropriate in the present case. For accurate polymer characterization, molecular weight distributions should be free of any mass discrimination effects imparted by the MALDI-cationization process, ion transmission to the analysis cell, ion excitation, or ion detection. The first discrimination possibility is beyond the scope of this article and is currently being investigated by others [12–16]. The last two do not pose a problem, provided that the experiment is done properly. However, there is some evidence that use of varying excitation conditions can shift apparent polymer distributions [27]. Sequential scanning of a range of frequencies for ion excitation could potentially allow pre-excited ions to lose energy during the duration of the excitation sweep, thereby decreasing their relative abundances. This case should produce distributions that seemingly shift in the direction of the sweep. Use of a high power excitation amplifier that is capable of delivering sufficient high voltage and fast frequency sweeps overcomes this problem. It is also possible to apply a SWIFT waveform for the range of frequencies of interest, producing a uniform excitation. An experiment was performed by polyisoprene 3000 and varying only the excitation conditions. Shown in Figure 2 is the series of spectra produced under positive sweep, negative sweep, and SWIFT excitation. Each spectrum represents the sum of 50 laser shots on a single sample spot. All three excitation methods were used throughout these experiments with preference given to chirp excitations, which yielded values with closer agreement of M_n and M_w and greater convenience of experimental tuning of the polymer distribution profiles when chirp excitations are employed.

By far, the major factor contributing to possible polymer mass discrimination is the trapping protocol. As pointed out by Hogan and Laude [28], there

can be a distinct discrimination effect in laser desorption–FTMS of polymers when the analysis cell is far from the desorption site. They varied the desorption distance by as much as 10 cm by using a variable desorption probe and found that, in the case of direct laser desorption, number average molecular weights varied by as much as 12% for polyethylene glycol 1500 ions. Here, ions are generated within 1 cm of the source trapping plate, eliminating this possibility [28]. Mass discrimination was investigated for two cases: low mass ions of high abundance for narrow mass distributions and high mass ions of lower abundance but wider mass distribution. It is to be understood that the terminology of narrow versus wide distributions refers to the effective mass range of the polymer from the lowest starting oligomer to the highest in the series. Because species with mass-to-charge ratio less than 2000 represent the majority of high resolution FTMS measurements, polyisoprene 650 was chosen to demonstrate subtle shifts in the average mass of detected polymer ion distributions as the ionization–trapping delay is sequentially increased. Figure 3 shows the gradual shift of the average to higher mass as the trap gate is closed at increasing time intervals of 10 μ s. Following the laser pulse and a 50- μ s delay with the source trap plate at ground and the solid conductance

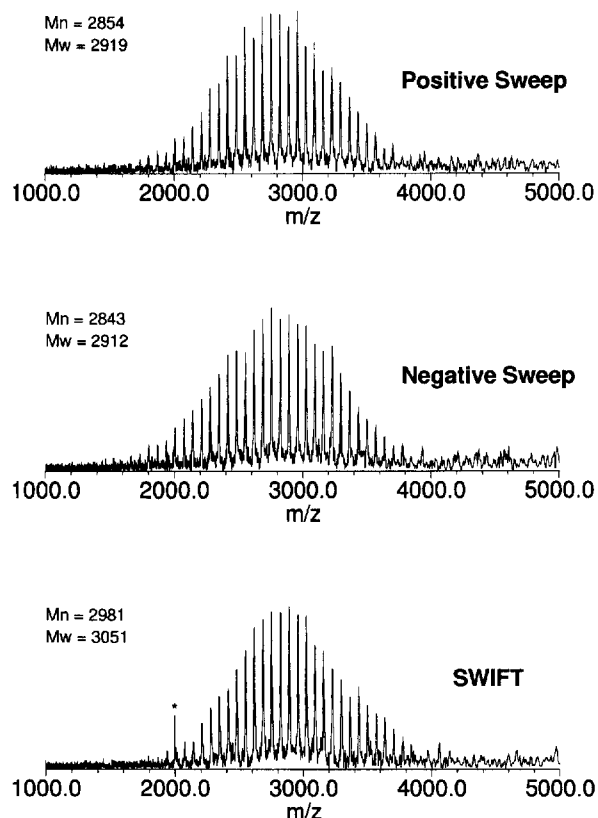


Figure 2. Excitation effects on polyisoprene 3000 showing that severe distortions do not exist. Each spectrum represents the co-addition of 50 single shot spectra. The asterisk denotes a noise artifact.

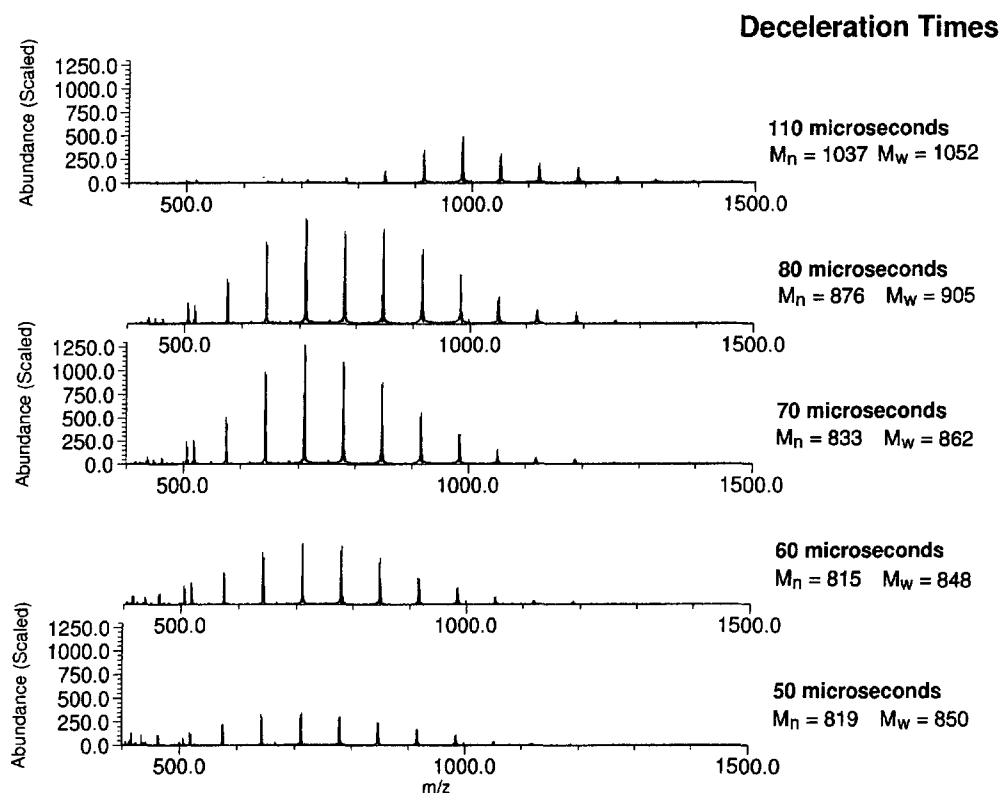


Figure 3. Polyisoprene 650 spectra taken at increasing gated trap times, showing the shift of the distribution centroid. Each spectrum is the sum of 25 scans.

limit plate at 9.5 V, low mass species are preferentially trapped. By use of an 80- μ s delay before applying static trapping voltages, the distribution reaches its maximum intensity. Use of longer delay periods serves only to decrease the overall ion signal as higher mass ions are the only species available to trap. Use of the "integral method" introduced by Dey et al. [26] produces a complete distribution profile (Figure 4) showing the characteristic polyisoprene 68.11-u repeat unit $-\text{[CH}_2\text{CH}=\text{C}(\text{CH}_3)\text{CH}_2\text{]}-$ plotted from $n = 4$ to 18. Comparison with the timed interval spectra reveals that with proper choice in timing, the experiment can proceed by using but a single timed deceleration, in this case 80 μ s (greatest ion abundance). Use of shorter times biases for lower masses and does not capture the majority of ions formed from the MALDI process; use of longer than optimal time biases in favor of the highest mass ions.

Because mass discrimination results from the electrostatic filtering effect, it is necessary to characterize to what extent this would be problematic for polymer characterization. Two functionally terminated polybutadiene samples of wide polydispersity were chosen for study. Both hydroxyl-terminated polybutadiene 1350 and phenyl-terminated polybutadiene 1300 (not shown) gave similar wide distributions starting below 1000 u and extending up to 4000 u. Spectra were taken at 5- μ s gated trap increments following the laser pulse, and the gated trap time was increased until there was no longer any observable signal. Two questions were

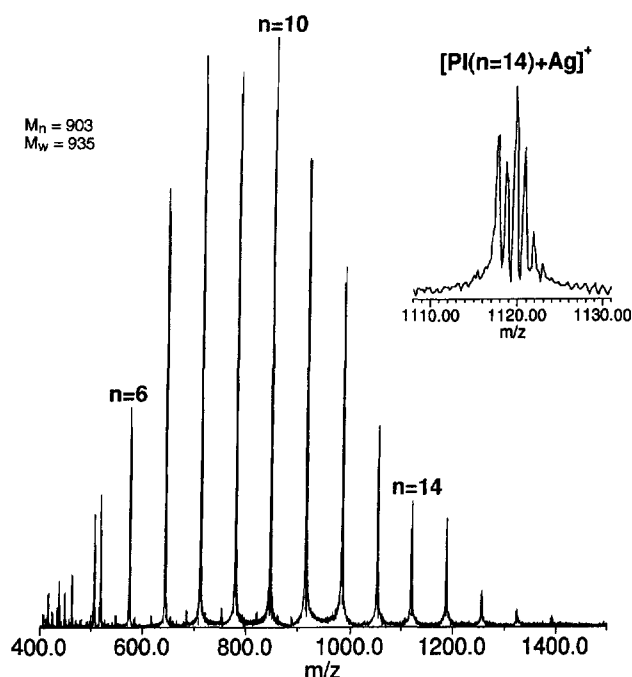


Figure 4. Co-addition of spectrum obtained for different gated trapping times between 50 and 110 μ s for polyisoprene 650. Resolving power is between 2000 and 3000. The inset shows the silver attached $n = 14$ oligomer.

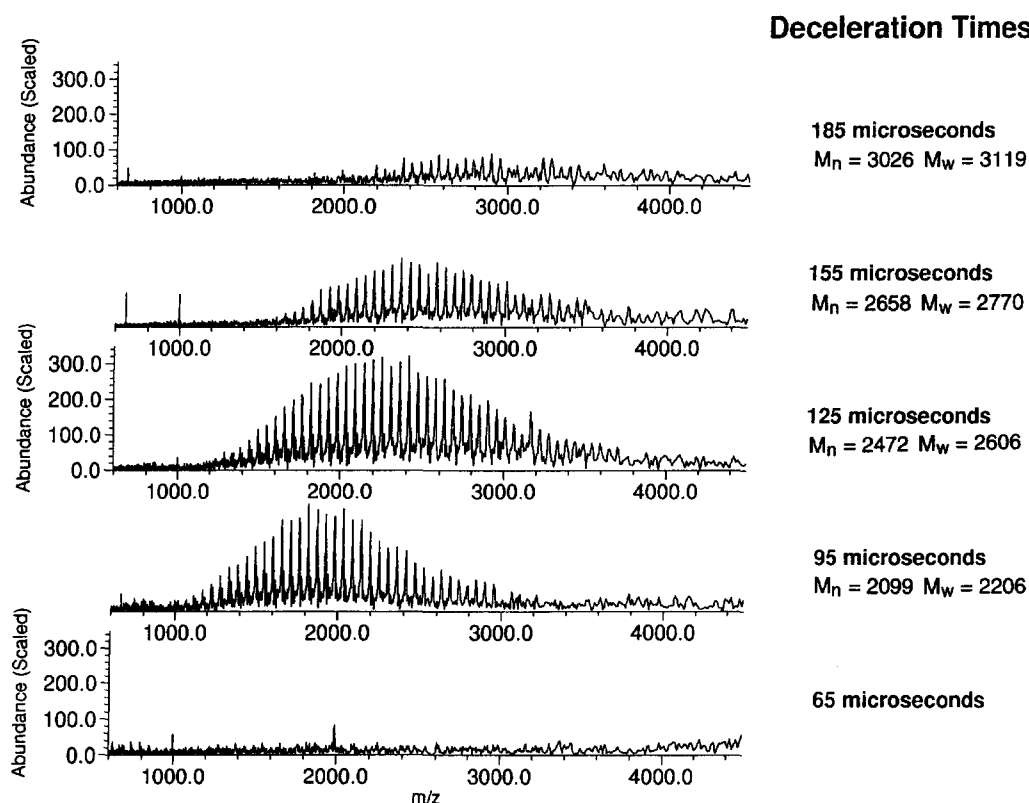


Figure 5. Spectra of hydroxyl-terminated polybutadiene 1350, taken at different gated trapping deceleration times following the laser pulse. Longer delays before applying static trapping voltages clearly show the time-of-flight effect of the ions entering the analysis cell. Each spectrum is the sum of 25 scans.

important. What was the observable mass range window? Further, what protocol was required to obtain a properly reconstructed spectrum of the wide mass polymer? In other words, how small are the steps for the gated trap increment, and does this produce any added discriminatory effects upon the overall spectrum? Figure 5 is the summary for hydroxyl-terminated polybutadiene 1350 showing co-added spectra taken at 65, 95, 125, 155, and 185 μ s following the laser pulse. Signal first appeared in the 65- μ s spectrum and was essentially gone in the 195- μ s spectrum (not shown). Spectra could be obtained by using any gated trap time within this 130- μ s range window! Subsets chosen from 27 spectra, for timed deceleration intervals varied systematically in 5- μ s increments, were combined by using different spacing values to see their cumulative effect on the polymer distribution. Surprisingly, the results produce similar spectra for the cases presented here, as shown in Figure 6. The spectra are the summed transient responses for combinations of 13, 4, and 3 co-added spectra corresponding to 10-, 30-, and 50- μ s increment spacings, respectively. The overall change appears to be subtle and lies at the extreme ends of the distribution where low abundance oligomers are not given equal weighting and/or lack sufficient overlap of the other distributions produced by single timed events. Therefore, the overall polymer does not appear to be as wide in mass range. These examples establish that polymers of wide mass distribution covering a

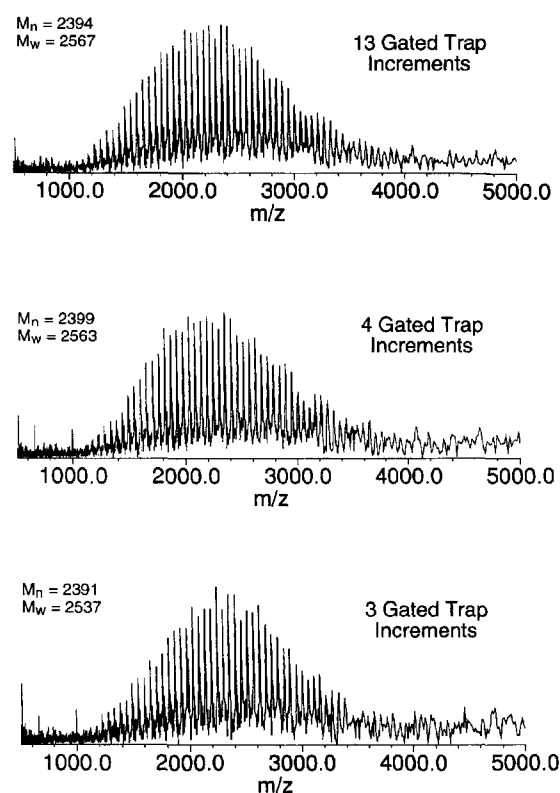


Figure 6. Spectra co-added in the time domain for hydroxyl-terminated polybutadiene 1350, which are the sums of 13 deceleration times (10- μ s spacing), 4 deceleration times (30- μ s spacing), and 3 deceleration times (50- μ s spacing).

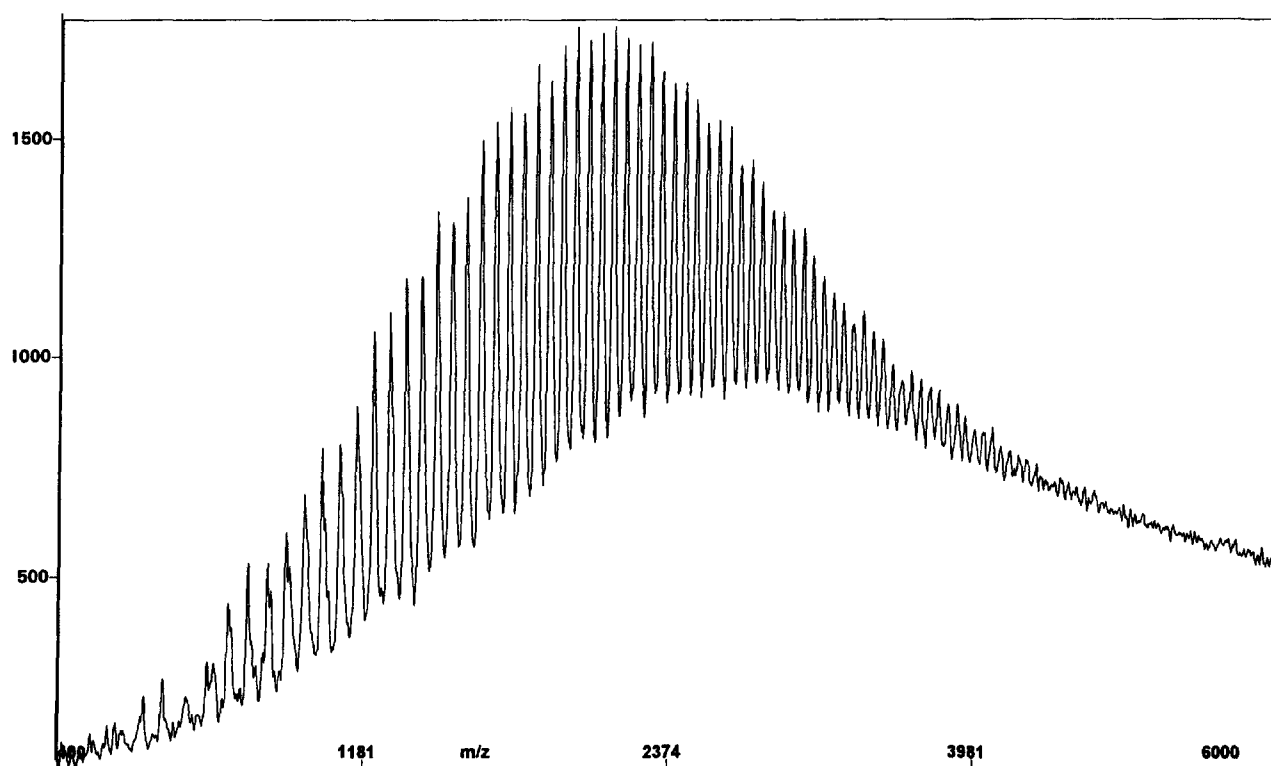


Figure 7. The spectrum of hydroxyl-terminated polybutadiene 1350 by using MALDI time-of-flight and an aliquot of the same sample used to obtain the spectra in Figure 5. The spectrum was obtained by using a Perceptive LaserTech Research MALDI-TOF instrument in the linear mode, employing a pulsed nitrogen laser operating at 337.1 nm (3-ns pulse width, 1-mm-diameter beam at probe, 10.5 μ J prefocussed). This instrument has a 1-m flight tube and an accelerating voltage of 30 keV was used. Fragment ions appear below m/z 800. The spectrum results from 100 averaged scans with 2-nm time resolution.

range larger than 2500 u and collected under a single trapped timing are likely to show mass discrimination at the extreme ends of their distributions. Readers are cautioned that wide mass distribution polymers beyond 2500 u in width will not yield a proper polymer distribution profile unless a proper increment set is taken. For comparison, a nontrap biasing time-of-flight spectrum of the same polymer sample appears in Figure 7. The spectrum clearly shows the presence of ions around 4000 u, indicating that their absence from the less sampled spectra shown in Figure 6 (middle and bottom) is problematic. For the highest accuracy in polymer characterization of wide mass polymers, increment spacing of at least 10 μ s is required.

Nonpolar Polymer Characterization

Because mass discrimination is seen only for polymer distributions wider than about 2500 u, a set of narrow distribution nonpolar polymer standards was examined. Figure 8 is the spectrum for polyisoprene 1000, showing a number average molecular weight of 1271.9 and a weight average molecular weight of 1288.4. This characterization was done by using the spectral peak heights of the oligomers. The use of peak heights for polymer characterization has been the subject of some

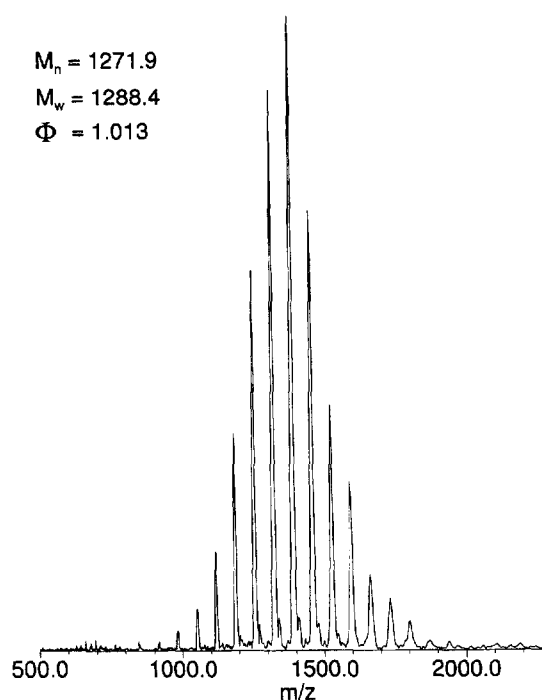


Figure 8. Silver cationized polyisoprene 1000 spectrum showing 68.11-u repeat unit. The spectrum is the sum of 16 single shot spectra.

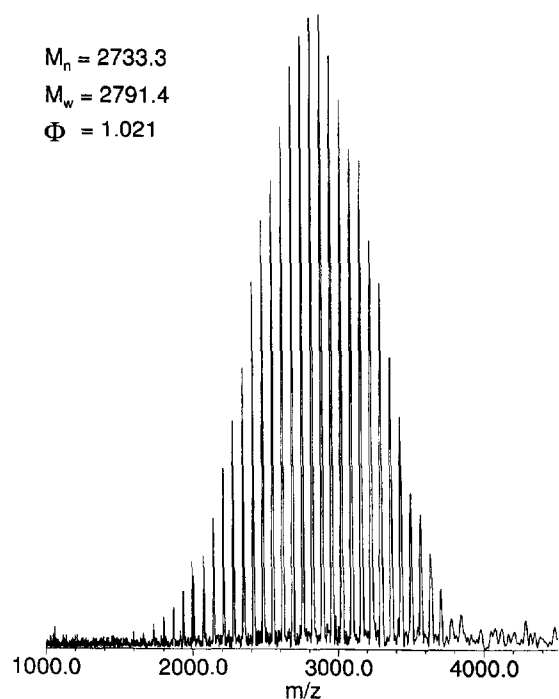


Figure 9. Silver cationized polyisoprene 2700. The spectrum results from 64 averaged scans.

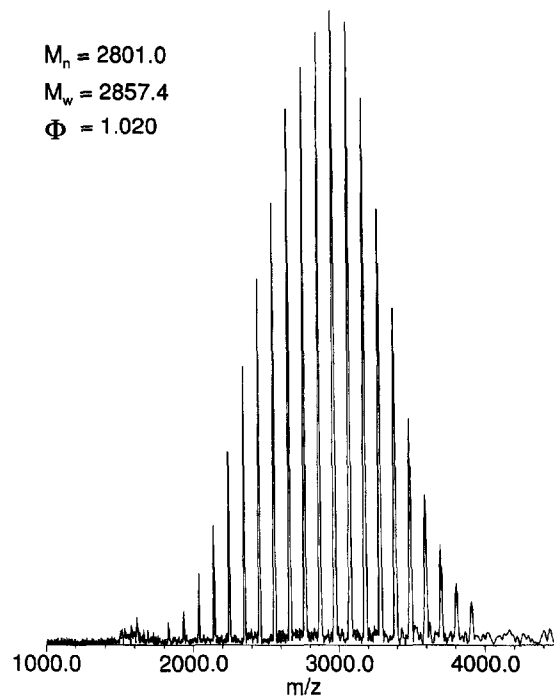


Figure 10. The spectrum of silver cationized polystyrene 2450 showing 104.14-u repeat unit. The spectrum results from 81 averaged scans and was obtained by using SWIFT excitation.

controversy because of the inherent decrease in resolution as mass is increased. Subtle changes in resolution can be seen here by examining the oligomers. The loss of intensity as mass increases might produce a slightly lower than expected molecular weight result owing to the greater contributions by the higher resolved low mass oligomers.

Figures 9-11 show spectra of nonpolar polymers with oligomers in the mass range between 1500 and 4000 u. They are spectra of polyisoprene 2700, polystyrene 2450, and polybutadiene 2800. Because there is no discrimination for narrow distributions less than 2500 u in range, in those cases all spectra could be obtained by using a single optimized gated trapping time. Ionization-trapping times were varied until an optimum signal intensity was produced. Spectra could then be signal averaged to improve S/N levels as desired. Polymer distribution values are mass corrected for silver attachment.

For the 3-T system used here, the upper mass limit for polymers is approximately m/z 6000. In unpublished results, it was possible to obtain a spectrum of singly charged ubiquitin (mass = 8565 u) in high abundance from single laser shots by using the gated deceleration protocol. A buffer gas helps cool ions and can enhance trapping efficiency. Figure 12 shows a spectrum of polybutadiene 5000 obtained with the help of a buffer nitrogen gas to aid in collisional cooling of the polymer during desorption. Efforts to extend polymer mass ranges in an FTMS are currently underway by using the five plate trapping method [24].

Conclusion

MALDI-FTMS has been applied to analysis of nonpolar polymers by using a 3-T Fourier transform mass spectrometer. By employing silver cationization and a pulse

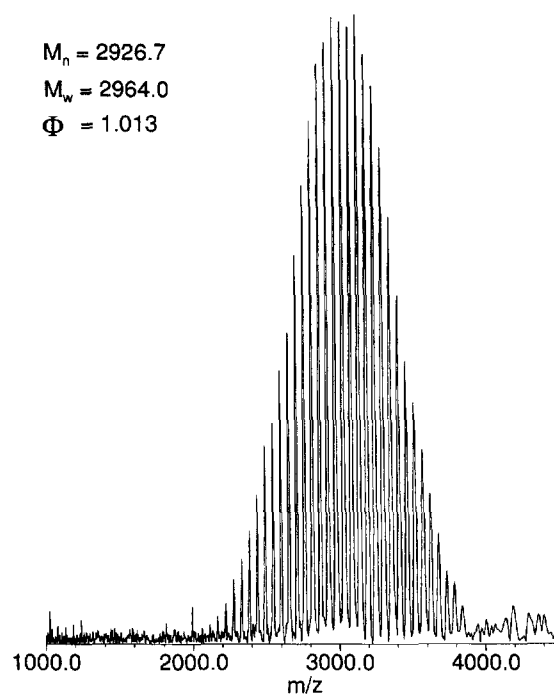


Figure 11. The spectrum of silver cationized polybutadiene 2800 showing 54.09-u repeat unit. The spectrum results from 64 averaged scans.

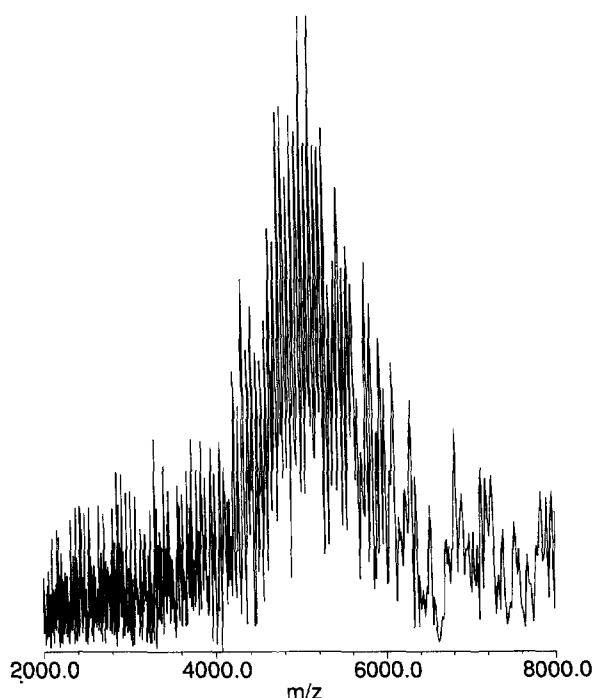


Figure 12. Silver cationized polybutadiene 5000. The spectrum results from 18 averaged scans. A 2-s argon pulse was used for ion cooling.

of argon gas for ion cooling during gated trapping, spectra with signals extending up to m/z 6000 can be obtained, which is the current polymer limit of our system. Use of higher magnetic fields should further extend this performance. Trapping discrimination is shown to exist for molecular weight distributions broader than about 2500 u by using the standard 2-in. cubic analysis cell. However, the integral procedure developed by Dey et al. [26] can be used to reconstruct the true polymer profiles through co-addition of signal transients obtained by using various gated deceleration times. Use of elongated cell designs may further improve the attainable mass window that currently discriminates polymer distributions wider than a 2500-u range. Finally, future work will focus on structural analysis of polymer systems. Because Fourier transform mass spectrometry is a trapped ion technique, it should be possible to use existing methods to both select individual oligomer species and perform structural analysis, leading to improved understanding of fundamental polymer processes.

Acknowledgments

This research was supported by the National Institutes of Health (grant no. GM-44606) and the National Science Foundation (grant no. CHE-92-01277).

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