Report on the 4th Annual NIST Polymer Mass Spectrometry Workshop: "Future Directions in Soft Ionization of Polymers"

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This year's annual workshop on polymer mass spectrometry was on the topic of "Future Directions in Soft Ionization of Polymers". The 2005 workshop was sponsored by the Polymers Division of the National Institute of Standards and Technology (NIST) and follows workshops held in 2002 [1, 2], 2003 [3], and 2004 [4]. The continuation of the series was made possible through the financial support of the American Society for Mass Spectrometry. This year's workshop was chaired by William E. Wallace (NIST, Gaithersburg, MD), Scott D. Hanton (Air Products and Chemicals, Inc., Allentown, PA), and Kevin G. Owens (Drexel University, Philadelphia, PA). The first day consisted of talks describing recent innovations in four major areas: Electrospray Ionization (ESI), Mass Spectrometry and Chromatography, Matrix-Assisted Laser Desorption/Ionization (MALDI), and New Methods for Soft Ionization. Each of the four sessions featured two invited speakers. The presentations given by the eight invited speakers will be summarized here. The second day consisted of open discussion periods covering NIST's role in the US Measurement System, development of a systematic nomenclature for polymer fragmentation, and a general problem solving session. The discussion that took place in the open problem solving session will not be reviewed here.

The opening talk was given by Professor John Fenn (Virginia Commonwealth University, Richmond, VA) on the origins of electrospray ionization of macromolecules. He began with a discussion of Otto Stern's experiments of the 1920s and his use of thermal beams of neutral atoms. He then moved into the science of free-jet expansion of beams and in particular of water molecule clusters, and brought us to the work of John Zeleny on electrospray of solvents and his demonstration of the effect of surface charge overcoming surface tension to form ever finer droplets. Later, Malcolm Dole worked on adding macromolecules to the solvent and, thus, began the field of electrospray ionization mass spectrometry. Dr. Fenn next described the experiments he and coworkers published in 1988 on the electrospray ionization of polyethylene glycols, eventually achieving intact, multiply charged PEG oligomers with masses in excess of 5 million Daltons. He concluded his talk with future directions for the electrospray technique and polymers including a discussion of electrospinning and the production of extremely fine polymer fibers. In particular, the electrospinning of colloidal suspensions yielded several previously unknown fiber morphologies. Lastly, Dr. Fenn concluded with a discussion of the entirely new area of electrospinning under alternating current and the new and as-yet unexplained morphologies that are produced.

Dr. Anthony T. Jackson (Imperial Chemical Industries, Redcar, United Kingdom) spoke on "Characterization of Polymers and Copolymers by Means of Tandem Mass Spectrometry: Development of Software to Aid Interpretation". He began with a description of the complex fragmentation spectrum achieved by electrospray tandem MS of the copolymer poly(HEMA)-co-poly(2-hydroxy methacrylate). He then went on to describe how the *Polymerator* software package developed by ICI and the University of Warwick could be used to identify rapidly the fragments produced. Thus far, the software has been successful at determining the fragment patterns of isoprenes, butadienes, ethylenes, propylene glycols, and methacrylates.

The second session on MS and Chromatography began with a talk by Dr. Jana Falkenhagen (Federal Institute for Materials Research and Testing {BAM}, Berlin, Germany) entitled "Characterization of Polyesters by the Coupling of Liquid Chromatography with MALDI and ESI Mass Spectrometry" and co-authored by her BAM colleagues S. Weidner, R.-P. Krueger, and U. Just. She began her talk with some examples where the use of size-exclusion chromatography, liquid adsorption chromatography, and liquid-adsorption chromatography at critical conditions were required to separate complex mixtures to simplify overly complex mass spectra. While these techniques are very powerful alone, when coupled to mass spectrometry Dr. Falkenhagen discussed two difficulties with performing chromatographic separations directly into an electrospray ionization mass spectrometer. The first is the proper choice of solvents that are suitable to both techniques. The second closely related point is the control of salts, which can have great effects on both the chromatographic and the electrospray step. One possible solution is to electrospray the eluent from the chromatographic step onto a MALDI target. MALDI is generally less salt sensitive than electrospray ionization.

The second talk in this session was given by Dr. Philip C. Price (Dow Chemical Company, Charleston, WV) and entitled "Polymers and GC/MS—A review of applications and why small molecules are important". Dr. Price began with a list of reasons as to why

Published online January 10, 2006

1044-0305/06/$32.00
doi:10.1016/j.jasms.2005.11.012
(J Am Soc Mass Spectrom 2006, 17, 280–282)

gas-chromatography coupled to mass spectrometry (GC-MS) is a useful tool for the analytical polymer chemist. These include the fact that it is fast, simple to perform, well understood, and has a high dynamic range enabling detection of a wide concentration range of small molecule additives often found in a polymer matrix. Dr. Price gave several examples, including the safety of food wrapped in plastic when exposed to microwaves for heating or gamma rays for preservation, as well as an analysis of small molecules that are given off by new automobile interiors and have human toxicity implications. The future of GC-MS lies partly in the analysis of so-called "active" or "intelligent" packaging. By adding desiccants, odor scavengers, or antimicrobial agents, plastic packaging can be an important value-added component to many consumer products. For such problems, pyrolysis-GC-MS has increased in importance. However, this area lacks both standard methods as well as a body of literature of well-controlled experiments.

During the lunch break, a meeting of Technical Working Activity 28 of the Versailles Project on Advanced Materials and Standards (VAMAS) on polymer MALDI MS standard method development was chaired by Dr. Charles M. Guttman (NIST, Gaithersburg, MD). Members from the United Kingdom, Germany, Japan, and the United States were present. Extension of American Society for Testing and Materials International (ASTM International) method D7134-05 to include other industrially-relevant materials beyond the original application to polystyrene was discussed. Reports of related polymer MS standards activities at the International Standards Organization (ISO) and the Deutsches Institut für Normung (DIN) were presented.

The first session after lunch was on the topic of Matrix-Assisted Laser Desorption/Ionization. Professor Kevin G. Owens (Drexel University, Philadelphia, PA) gave the opening address entitled "How well do we REALLY understand MALDI?" Professor Owens discussed the need for greater scientific understanding of the "black art" of MALDI sample preparation. His talk was rhetorical in nature, asking as many questions as it set out to answer. He felt that there was consensus in the community that the MALDI plume was a reaction vessel that controlled the chemistry of polymer ionization. According to this view, preformed ions are not required; instead the supersonic molecular beam created by the laser pulse initiates the ionization of the analyte. An open question remains, however, as to whether polymer analyte molecules need to be in solid solution with the matrix. Recent work using matrix-enhanced secondary ion mass spectrometry (ME-SIMS) suggests that the analyte can be either on or in the matrix and still yield a good spectrum. The true nature of the MALDI sample remains one of the outstanding questions in polymer MS research.

Dr. Richard M. Knochenmuss (Novartis Research Institutes, Basel, Switzerland) gave the second talk in this session entitled "Looking Deeper into MALDI: Understanding and Predicting MALDI Phenomena using Numerical Models", where he described further developments of his two-step continuum model. In the two-step model, the first step consists of primary ionization of sample molecules (primarily the matrix molecules) during and shortly after the laser pulse. The second step involves ion-molecule reactions in the expanding plume. In the expanding plume, excited (but still neutral) matrix molecules can exchange energy to form neutral ground-state molecules and matrix ions. These ions in turn interact with analyte via electron transfer, proton transfer, or cationization. The latter case is most important to polymer MS, where metal cationization of the polymer is a critical step. Dr. Knochenmuss gave examples of his model applied to mixtures of polycyclic aromatic hydrocarbons. He was able to predict quantitatively ion yields for individual components of a mixture as a function of matrix to analyte ratio. He next described experiments where the effect of the sample-holder material (gold or stainless steel) affected the filling of the molecular orbitals of the matrix molecule (through interaction with the Fermi level of the metal); these interactions can greatly enhance the matrix ion yield. These substrate effects were found to increase ion yield of the matrix molecule by two orders of magnitude.

The final session of the workshop was on the subject of New Methods for Soft Ionization. The first speaker was Dr. Andre Venter (Purdue University, West Lafayette, IN). His talk was entitled "Desorption Electrospray Ionization (DESI) including Synthetic Polymer Applications" and his Purdue co-authors were Marcela Nefliu and Graham R. Cooks. DESI is an ambient soft ionization technique that directs the electrospray stream at a glancing angle onto a surface of interest from a distance of anywhere between 1 and 8 mm. The electrospray voltage is in the range of 1 to 8 kV and the carrier gas is heated to between 200 and 350 °C. Many solvents can be used; examples are water, methanol, and water-methanol mixtures. Dr. Venter then gave a host of examples of DESI used on a wide variety of materials including data taken from entire *E. coli* as a method of species identification, and the explosive RDX (also known as "Research Department Explosive" as invented by the British after World War I) measured directly on a contaminated surface, useful for homeland security. In the area of synthetic polymers he showed a poly(ethylene glycol) of 3000 u. An intriguing future direction for this technique is in the area of "reactive DESI" where chemically reactive species are placed in the electrospray solvent and react with trace surface contaminants to enhance their signal strength. This method has the potential to increase the dynamic range of DESI.

The final talk of the day was given by Dr. H. Dupont Durst (U.S. Army Edgewood Chemical Biological Center, Aberdeen, MD) and was entitled "The DART Revolution: Fast, Non-Contact, Soft Ionization without Sample Preparation" with co-authors R. B. Cody and

J. A. Laramée. The advantages of DART are spelled out in its acronym: direct analysis in real time. It is a technique that employs a stream of metastable noble gas atoms to lift simultaneously molecules off a surface and ionize them. DART requires no sample preparation, the sample does not need to be placed in vacuum, no solvents or chemicals are needed; only a tank of inert gas is required. The technique can create a mass spectrum in under a minute. The sampling is non-contact, and the technique can detect even extremely low-volatility species. It uses neutral, excited metastable inert gases to transfer energy to the sample surface. In the examples given by Dr. Durst, metastable 2^3S helium was used. With de-excitation energy of 19.8 eV, metastable helium can ionize just about any organic species. Examples were given of real-time analysis of nylon 12 and poly (cyanoacrylate) where the sample could be positively identified in under a minute.

The second day of the workshop began with a presentation of Dr. Dennis Swyt (NIST, Gaithersburg, MD) on the subject of NIST and the U.S. Measurement System (USMS). NIST is currently performing a comprehensive assessment of the current and future needs of the USMS. A detailed description of this effort may be found at www.nist.gov/usms. The USMS is defined as the sum of all entities that make measurements, validate measurements, and rely on others' measurements, to perform their essential functions. These functions can be commerce, trade, national defense, or any other similar arena.

The challenge for the Workshop attendees was to distill their collective efforts into a succinct statement of what are the current and future barriers to the use of mass spectrometry in the polymer industry. The challenge most often brought up by the attendees was the persistent and conflicting measures of polymer molecular properties given by different analytical techniques. Studies of systematic uncertainties and method validation were seen as the most useful solution. An example of the measurement challenges in determining the polymer single-chain properties used in wax-based color toners for reprographics was extensively discussed. A "measurement need" white paper will be drafted by the workshop chairs and submitted to the NIST USMS Project. This white paper will be placed on the web at www.nist.gov/maldi for public comment.

The second topic for discussion was the need for a consistent nomenclature in the area of polymer fragmentation. Dr. Philip Price (Dow Chemical, Charleston, WV), Professor Chrys Wesdemiotis (University of Akron, OH), and Dr. Anthony T. Jackson (ICI, Redcar, U.K.) were the panelists in a discussion that resulted in the proposal of an entirely new nomenclature. A description of this nomenclature may be found at polyfragnotation.wikispaces.com. This web site allows for public comment on the new scheme. At the next American Society for Mass Spectrometry meeting in Seattle, WA (May 28–June 1, 2006), a poster will be presented, and further discussion will be held at the Polymeric Materials Interest Group Workshop. Comments from the polymer MS community are welcomed and encouraged.

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