FINAL TECHNICAL REPORT

NASA Grant #NAG5-9384
Program: Space Astrophysics Research and Analysis (SARA)

"Molecular Carbon in the Galaxy: Laboratory and Observational Studies"
(Award Period: 04/01/00 - 03/31/03)

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Final Report

I. A Laboratory Study of the H_3^+-e^- Recombination Rate

In a collaboration with the Mats Larsson group from Stockholm, we carried out a new measurement of the rate of dissociative recombination of H_3^+, using a new pulsed supersonic beam source of rotationally cold H_3^+. This source was first designed and characterized in our lab by IR cavity ringdown spectroscopy, determining a rotational/translational temperature of 20-60K, depending on conditions. This new source was then taken to Stockholm for the recombination rate studies at the CRYRING storage ring. The recombination rate constant measured against temperature yields values consistent with the most recent calculations, whereas previous experimental measurements varied over a range of 10^4 and were poor agreement with theory.

This is a crucial achievement for understanding the ion chemistry of diffuse clouds. Moreover, this result in combination with recent observations implies a greatly enhanced (factor of 40) cosmic ray ionization rate in a diffuse cloud (ζ Persei) relative to previous studies. The implications of this are discussed in our recent *Nature* paper [B.J. McCall, A.J. Huneycutt, R.J. Saykally, T.R. Geballe, N. Djuric, G.H. Dunn, J. Semaniak, O. Novotny, A. Al-Khalili, A. Ehlerding, F. Hellberg, S. Kalhori, A. Neau, R. Thomas, F. Osterdahl, and M. Larsson, "An enhanced cosmic-ray flux towards ζ Persei inferred from a laboratory study of the H_3^+-e^- recombination rate," *Nature* **422**, 500-502 (2003)].

II. IR Cavity Ringdown Spectroscopy of Carbon Clusters

We have continued to develop the requisite technology for extending cavity ringdown methods throughout the mid-IR – a necessary step for a systematic study of carbon clusters. Our pulsed high resolution (Alexandrite laser-based) system has been refurbished with a new technology for triggering the flashlamps while in cavity lock. This has resulted in much improved reliability and spectral bandwidth (now < 60 MHz), but somewhat degraded ability for externally locking to the laser vaporization source. We are currently working on schemes to improve the latter. A paper describing the design, construction, and performance of our pulsed, high resolution mid-IR cavity ringdown system (largely based on a study of the C_9 cluster) was publiched [R.N. Casaes, R.A. Provencal, J.B. Paul, and R.J. Saykally, "High resolution pulsed infrared cavity ringdown spectroscopy: Application to laser ablated carbon clusters," *J. Chem. Phys.* **116**, 6640-6647 (2002)].

III. Mid-IR Water Recombination Lasers

We reported the discovery of a large number of mid-IR lasing transitions in pulsed supersonic plasmas containing helium and H_2O [*Chem. Phys. Lett.* **338**, 277-284 (2001)]. This work has now been extended to pure hydrogen discharges, where over 12 IR laser lines have been discovered. Moreover, additional transitions in He/H_2O discharges have been found and tentatively assigned to the H_2O^+ ion. We believe that these lasers are driven by electron-ion recombination, and that this mechanism may be operative in appropriate interstellar sources.

IV. Single Photon Infrared Emission Spectroscopy (SPIRES) of PAHs and PAH Cations

We have published the first detection of laboratory IR emission spectra from gaseous PAH cations [*Phys. Rev. Lett.* **86**, 5691 (2001)]. The spectra of pyrene cation, measured by our SPIRES spectrometer in an ion beam, generally agree well with both UIR bands and with matrix isolating spectra. We have also published a detailed report on this work, additionally describing spectra of dehydrogenated PAH cations observed in the SPIRES experiment, as well as the design of the experiment itself [H.-S. Kim, and R.J. Saykally, "Single Photon Infrared Emission Spectroscopy of Gaseous Polycyclic Aromatic Hydrocarbon Cations: A Direct Test for Proposed Carriers of the Unidentified Infrared Emission Bands," *Astrophys. J. Supp. Series*, **143**:455-467 (2002); H.-S. Kim, and R.J. Saykally, "An ion beam reflectron/ single photon infrared emission (SPIRE) spectrometer for the study of gas phase PAH ions: testing proposed carriers of the unidentified infrared emission bands (UIRs)," *Rev. Sci. Instrum.* **74**, 2488 (2003)].

Graduate Students Supported by this Grant

Raphael Casaes (Ph.D. expected 8/03)

Alex Huneycutt (Ph.D. expected 6/03)

Don Wagner (Ph.D. 2001)

Postdoctorals Supported by this Grant

H.-S. Kim (Northwestern)

E.A. Michael (U. Cologne)

Publications Supported by NASA (numbers correspond to complete list)

239. T.F. Giesen, U. Berndt, G. Fuchs, G. Winnewisser, R.A. Provencal, F.N. Keutsch, A. Van Orden, and R.J. Saykally, "IR Laser Spectroscopy of Carbon Clusters," *Proceedings of the Nobel Symposium 117 on The Physics and Chemistry of Clusters, Visby, Sweden, E.E.B. Campbell and M. Larsson (eds.)*; pp. 309-310 (2001).

240.* T.F. Giesen, U. Berndt, K.M.T. Yamada, G. Fuchs, R. Schieder, G. Winnewisser, R.A. Provencal, F.N. Keutsch, A. Van Orden, and R.J. Saykally, "Detection of the Linear Carbon Cluster C_{10}: Rotationally Resolved Diode Laser Spectroscopy," *ChemPhysChem* **4**, 242-247 (2001).

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241. T.F. Giesen, A.O. Van Orden, J.D. Cruzan, R.A. Provencal, R. Gendriesch, F. Lewen, G. Winnewisser, R.T. Boreiko, A.L. Betz, and R.J. Saykally, "Interstellar Detection of CCC and High Precision Laboratory Measurements near 2 THz," *Astrophys. J. Lett.* **551**:L181-L184 (2001).

243. E.A. Michael, C.J. Keoshian, D.R. Wagner, S.K. Anderson, and R.J. Saykally, "Infrared Water Recombination Lasers," *Chem. Phys. Lett.* **338**, 277-284 (2001).

244. R.J. Saykally and R. Casaes, "Cavity ringdown technique measures absorption," *Laser Focus World* **37**, 159-162 (2001).

247. H.-S. Kim, D.R. Wagner, and R.J. Saykally, "Single Photon Infrared Emission Spectroscopy of the Gas Phase Pyrene Cation: Support for a Polycyclic Aromatic Hydrocarbon Origin of the Unidentified Infrared Emission Bands," *Phys. Rev. Lett.* **86**, 5691 (2001).

249. E. Michael, C.J. Keoshian, S.K. Anderson, and R.J. Saykally, "Rotational transitions in excited vibrational states of D_2O," *J. Mol. Spec.* **208**, 219-223 (2001).

254. R.N. Casaes, R.A. Provencal, J.B. Paul, and R.J. Saykally, "High resolution pulsed infrared cavity ringdown spectroscopy: Application to laser ablated carbon clusters," *J. Chem. Phys.* **116**, 6640-6647 (2002).

260. R.N. Casaes and R.J. Saykally, "Spectroscopy (CRLAS)," *The McGraw-Hill 2002 Yearbook of Science & Technology*, Mark D. Licker, editor, pp. 331-333 (2001).

270. H.-S. Kim, and R.J. Saykally, "Single Photon Infrared Emission Spectroscopy of Gaseous Polycyclic Aromatic Hydrocarbon Cations: A Direct Test for Proposed Carriers of the Unidentified Infrared Emission Bands," *Astrophys. J. Supp. Series*, **143**:455-467 (2002).

273. B.J. McCall, A.J. Huneycutt, R.J. Saykally, C.M. Lindsay, T. Oka, M. Fushitani, Y. Miyamoto, and T. Momose, "Stimulated Stokes downconversion in liquid and solid parahydrogen," *Applied Physics Letters* **82**, 1350-1352 (2003).

275. H.-S. Kim, and R.J. Saykally, "An ion beam reflectron/ single photon infrared emission (SPIRE) spectrometer for the study of gas phase PAH ions: testing proposed carriers of the unidentified infrared emission bands (UIRs)," *Rev. Sci. Instrum.* **74**, 2488 (2003).

Invited Lectures (numbers correspond to complete list)

282. "Some "Radical" New Experiments in Molecular Spectroscopy," 26th International Symposium on Free Radicals, "La Cittadella," Assisi, Italy; September 2-7, 2001.

283. "Single Photon IR Emission Spectroscopy of PAH^+ Cations," 3eme Cycle Workshop, Hotel de Champéry, Valais, Switzerland; September 9-13, 2001.

284. "Cavity Ringdown Spectroscopy," 3eme Cycle Workshop, Hotel de Champéry, Valais, Switzerland; September 9-13, 2001.

285. "IR Cavity Ringdown Spectroscopy," 3eme Cycle Workshop, Hotel de Champéry, Valais, Switzerland; September 9-13, 2001.

291. "High Resolution Pulsed IR Cavity Ringdown Spectroscopy: Application to Laser Ablated Carbon Clusters," Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy, PITTCON 2002, New Orleans, LA; March 17-22, 2002.

292. "Molecular Carbon in the Galaxy: New Laboratory and Observational Studies," Astrobiology Science Conference 2002, NASA Ames Research Center, Moffett Field, CA; April 7-11, 2002.

293. "High Resolution Pulsed IR Cavity Ringdown Spectroscopy: Application to Laser Ablated Carbon Clusters," Moses Gomberg Lecture series, University of Michigan, MI; April 18, 2002.

294. "Molecular Carbon in the Galaxy: New Laboratory and Observational Studies," NASA Laboratory Astrophysics Workshop (LAW), NASA Ames Research Center, Moffett Field, CA; May 1-3, 2002.

295. "Single Photon Counting InfraRed Emission Spectroscopy of PAH+ Cations: Progress in Identifying the Carriers of the UIR Bands," Colloquium, Max-Planck-Institut (MPI), Garching, Germany, July 15, 2002.

300. "Carbon Chains and PAH Ions in Space and in the Lab," CIPS Workshop, Space Sciences Laboratory, UC Berkeley, CA; November 13, 2002.

CURRICULUM VITAE

Richard James Saykally
Professor of Chemistry
Department of Chemistry, University of California, Berkeley, CA 94720-1460, U.S.A.
(September 10, 1947; Rhinelander, Wisconsin)

- Professional Interests: Laser spectroscopy, X-ray spectroscopy, astrophysics, liquid surface chemistry, clusters, intermolecular forces, femtosecond chemical imaging microscopy, biophysics, water, science education.
- Research advisor for 41 Ph.D. and 6 M.S. Graduates and 25 Postdoctorals.
- Coauthor of over 250 Scientific Articles.

Education B.S. (1970) University of Wisconsin – Eau Claire
Ph.D. (1977) University of Wisconsin – Madison (with R. C. Woods)
Postdoctoral (1977-79) NIST – Boulder (with K. M. Evenson)

AWARDS, HONORS, LECTURESHIPS
National Research Council Postdoctoral Fellowship – 1977
Camille and Henry Dreyfus Award – 1979
NSF Presidential Young Investigator – 1984-88
UC Berkeley Miller Research Professor – 1985-86
Fellow – Royal Society of Chemistry – 1986
UW-Eau Claire Distinguished Alumnus Award – 1987
Bergman Lectureship, Yale University – 1987
Merck-Frost Lectureship, University of British Columbia – 1988
Bomem Michelson Prize for Spectroscopy (Coblentz Society) – 1989
E.K. Plyler Prize for Molecular Spectroscopy (APS) – 1989
Fellow – American Physical Society – 1989
E.R. Lippincott Medal for Spectroscopy (OSA, SAS) – 1992
Distinguished Teaching Award – University of California-Berkeley – 1992
Harrison Howe Award (ACS-Rochester Section) – 1992
Bourke Medal, U.K. Royal Society of Chemistry – 1992
L.J. Bircher Lectureship, Vanderbilt University – 1993
Fellow – Optical Society of America – 1994
Churchill Fellowship, Cambridge University – 1995
Harry Emmett Gunning Lectureship, University of Alberta – 1995
Fellow – American Academy of Arts and Sciences – 1995
Humboldt Senior Scientist Award – 1995
Samuel M. McElvain Lectureship, University of Wisconsin-Madison – 1995
UC Berkeley Miller Research Professor – 1997-98
Pittsburgh Spectroscopy Award – 1999
Bryce Crawford Lectureship, University of Minnesota – 1999
Frontiers in Chemical Research, Distinguished Lecturer, Texas A&M University – 1999
Member – National Academy of Sciences – 1999
Sesquicentennial Colloquium Lecturer in Chemistry, University of Utah – 2000
Irving Langmuir Award in Chemical Physics (ACS) – 2000
Rayson Huang Distinguished Lecturer, University of Hong Kong – 2000
Dreyfus Distinguished Lecturer in Chemistry, Dartmouth College – 2001
Centenary Medal, U.K. Royal Society of Chemistry – 2001
Fellow – American Association for the Advancement of Science – 2001
Moses Gomberg Lecturer, University of Michigan – 2002
Distinguished Lecturer, Molecular Sciences Forum, Chinese Academy of Sciences – 2002

PROFESSIONAL ACTIVITIES

Co-Director – "Science for Science Teachers (S_4ST)," NSF Summer Training Institute for Junior High School Science Teachers – 1989-93

Co-Director – "Prime Science," NSF Junior High School Curriculum Development Project – 1992-present

Advisory Committee – Radio Astronomy Laboratory (UCB) – 1996-present

Canvassing Committee – Irving Langmuir Award (ACS) – 1996-2001

Executive Committee – Division of Chemical Physics (APS) – 1995-1999

Laser Science Topical Group Fellowship Committee (APS) – 1993-present

Selection Committees – E.K. Plyler Prize (APS), Ellis R. Lippincott Medal (OSA)

Editorial Advisory Board – The Journal of Physical Chemistry – 2003

Journal Editorial Review Boards – Molecular Physics (1983-present), Spectroscopy (1986-present), Review of Scientific Instruments (1987-90), Chemical Physics Letters (1987-present), Journal of Chemical Physics (1993-95), Journal of Molecular Spectroscopy (1995-present), European Journal of Chemical Physics and Physical Chemistry (2000-present), Journal of Physical Chemistry (2002-present), Cambridge Services and Molecular Science, Cambridge University Press (2003)

Triennial Oversight Committee for the NSF – 1992

Executive Committee – Western Spectroscopy Conference – 1982-85

International Steering Committee – Twelfth International Conference on Laser Spectroscopy (TWICOLS '95)

Board of Directors, Space Sciences Laboratories, UC-Berkeley 1983-86

Member – American Association of University Professors, American Association for the Advancement of Science, American Chemical Society

University of California – Committee on Teaching, Committee on Research, Committee on Committees, Budget Committee

PROFESSIONAL EXPERIENCE

Assistant Professor, University of California-Berkeley (1979-83)

Associate Professor, University of California-Berkeley (1983-86)

Principal Investigator, Lawrence Berkeley Laboratory (1983-91)

Professor, University of California-Berkeley (1986-99)

Vice Chairman, University of California-Berkeley (1988-91)

Class of 1932 Distinguished Chair, UC-Berkeley (1999-present)

Visiting Professor: University of Nijmegen (1991), Max-Planck-Institute for Fluid Dynamics-Göttingen (1991), Cambridge University (1995), University of Montpellier (1996), Technical University-Munich (1996-97), Max-Planck Institute for Solid State Physics-Stuttgart (1999), Physics Institute, University of Cologne (2000), Fritz Haber Institute-Berlin (2001) , Max-Planck-Institute for Extraterrestrial Physics-Munich (2002), Max-Planck-Institute for Biochemistry-Martinsried (2002)

PUBLICATIONS 2000-present (numbers correspond to complete list)

Richard J. Saykally

225. R.A. Provencal, R.N. Casaes, K. Roth, J.B. Paul, C.N. Chapo, R.J. Saykally, G.S. Tschumper, and H.F. Schaefer, III, "Hydrogen Bonding in Alcohol Clusters: A Comparative Study by Infrared Cavity Ringdown Laser Absorption Spectroscopy," *J. Phys. Chem. A* **104**, 1423 (2000).

226.* R.D. Schaller, C. Roth, D.H. Raulet, and R.J. Saykally, "Near-field Second Harmonic Imaging of Granular Membrane Structures in Natural Killer Cells," *J. Phys. Chem. B* **104**, 5217 (2000).
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227. L.B. Braly, J.D. Cruzan, K. Liu, R.S. Fellers, and R.J. Saykally, "Terahertz Laser Spectroscopy of the Water Dimer Intermolecular Vibrations. I. $(D_2O)_2$," *J. Chem. Phys.* **112**, 10293 (2000).

228. L.B. Braly, K. Liu, M.G. Brown, F.N. Keutsch, R.S. Fellers, and R.J. Saykally, "Terahertz Laser Spectroscopy of the Water Dimer Intermolecular Vibrations. II. $(H_2O)_2$," *J. Chem. Phys.* **112**, 10314 (2000).

229. D.R. Wagner, and R.J. Saykally, "Ringing the changes," *Chemistry in Britain* **36**, 47-49 (July 2000).

230. R.D. Schaller, J.C. Johnson, and R.J. Saykally, "Nonlinear Chemical Imaging Microscopy: Near-Field Third Harmonic Generation Imaging of Human Red Blood Cells," *Analytical Chemistry* **72**, 5361-5364 (2000).

231. K.R. Wilson, J.G. Tobin, A.L. Ankudinov, J.J. Rehr, and R.J. Saykally, "Extended X-Ray Absorption Fine Structure from Hydrogen Atoms in Water," *Phys. Rev. Lett.* **85**, 4289 (2000).

232. D.R. Wagner, HS. Kim, and R.J. Saykally, "Peripherally Hydrogenated Neutral Polycyclic Aromatic Hydrocarbons as Carriers of the 3 Micron Interstellar Infrared Emission Complex: Results from Single Photon Infrared Emission Spectroscopy," *Astrophys. J.* **545**:854-860 (2000).

233.* N. Goldman, R.S. Fellers, C. Leforestier, and R.J. Saykally, "Water Dimers in the Atmosphere: Equilibrium Constant for Water Dimerization From the VRT (ASP-W) Potential Surface," *J. Phys. Chem. A* **105**, 515-519 (2001).
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234. F.N. Keutsch, E.N. Karyakin, A. van der Avoird, and R.J. Saykally, "The 583.2 GHz Torsional Hot-Band of $(D_2O)_3$," *J. Chem. Phys.* **114**, 3988-3993 (2001).

235. F.N. Keutsch, M.G. Brown, P.B. Petersen, M. Geleijns, A. van der Avoird, and R.J. Saykally, "Terahertz VRT Spectroscopy of Water Clusters in the Translational Band Region of Liquid Water," *J. Chem. Phys.* **114**, 3994-4004 (2001).

236. F.N. Keutsch, R.S. Fellers, M.R. Viant, and R.J. Saykally, "Far-IR VRT Spectroscopy of Water Clusters in the Librational Band Region of Liquid Water," *J. Chem. Phys.* **114**, 4005-5015 (2001).

237.* R.D. Schaller, and R.J. Saykally, "Near-field Sum Frequency Generation Imaging of CVD Zinc Selenide," *Langmuir* **17**, 2055-2058 (2001).
***Cover Article.**

238. R.J. Saykally, "Water Clusters: Building Up the Liquid One Step at a Time," *Proceedings of the Nobel Symposium 117 on The Physics and Chemistry of Clusters, Visby, Sweden, E.E.B. Campbell and M. Larsson (eds.)*; pp. 206-218 (2001).

239. T.F. Giesen, U. Berndt, G. Fuchs, G. Winnewisser, R.A. Provencal, F.N. Keutsch, A. Van Orden, and R.J. Saykally, "IR Laser Spectroscopy of Carbon Clusters," *Proceedings of the Nobel Symposium 117 on The Physics and Chemistry of Clusters, Visby, Sweden, E.E.B. Campbell and M. Larsson (eds.)*; pp. 309-310 (2001).

240.* T.F. Giesen, U. Berndt, K.M.T. Yamada, G. Fuchs, R. Schieder, G. Winnewisser, R.A. Provencal, F.N. Keutsch, A. Van Orden, and R.J. Saykally, "Detection of the Linear Carbon Cluster C_{10}: Rotationally Resolved Diode Laser Spectroscopy," *ChemPhysChem* **4**, 242-247 (2001).
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242.* K.R. Wilson, B. Rude, T. Catalano, R. Schaller, J.G. Tobin, D.T. Co, and R.J. Saykally, "X-Ray Spectroscopy of Liquid Water Microjets," *J. Phys. Chem. B* **105**, 3346-3349 (2001).
***Cover Article.**

243. E.A. Michael, C.J. Keoshian, D.R. Wagner, S.K. Anderson, and R.J. Saykally, "Infrared Water Recombination Lasers," *Chem. Phys. Lett.* **338**, 277-284 (2001).

244. R.J. Saykally and R. Casaes, "Cavity ringdown technique measures absorption," *Laser Focus World* **37**, 159-162 (2001).

245.**T.-Q. Nguyen, B.J. Schwartz, R.D. Schaller, J.C. Johnson, L.F. Lee, L.H. Haber, and R.J. Saykally, "Near-Field Scanning Optical Microscopy (NSOM) Studies of the Relationship Between Interchain Interactions, Morphology, Photodamage and Energy Transport in Conjugated Polymer Films," *J. Phys. Chem. B* **105**, 5153-5160 (2001).
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246. F.N. Keutsch, R.S. Fellers, M.G. Brown, M.R. Viant, P.B. Petersen, and R.J. Saykally, "Hydrogen Bond Breaking Dynamics of the Water Trimer in the Translational and Librational Band Region of Liquid Water," *J. Am. Chem. Soc.* **123**, 5938-5941 (2001).

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249. E. Michael, C.J. Keoshian, S.K. Anderson, and R.J. Saykally, "Rotational transitions in excited vibrational states of D_2O," *J. Mol. Spec.* **208**, 219-223 (2001).

250. F.N. Keutsch, and R.J. Saykally, "Water Clusters: Untangling the mysteries of the liquid, one molecule at a time," *PNAS* **98**, 10533-10540 (2001).

251. L.F. Lee, R.D. Schaller, L.H. Haber, and R.J. Saykally, "High Spatial Resolution Imaging with Near-field Scanning Optical Microscopy in Liquids," *Anal. Chem.* **73**, 5015 (2001).

252.* J.C. Johnson, H. Yan, R.D. Schaller, L.H. Haber, P. Yang, and R.J. Saykally, "Single Nanowire Lasers," *J. Phys. Chem. B* **105**, 11387-11390 (2001).

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253.**K.R. Wilson, M. Cavalleri, B.S. Rude, R.D. Schaller, A. Nilsson, L.G.M. Pettersson, N. Goldman, T. Catalano, J.D. Bozek, and R.J. Saykally, "Characterization of hydrogen bond acceptor molecules at the water surface using near-edge x-ray absorption fine-structure spectroscopy and density functional theory," *J. Phys.: Condens. Matter* **14**, L221-L226 (2002).

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254. R.N. Casaes, R.A. Provencal, J.B. Paul, and R.J. Saykally, "High resolution pulsed infrared cavity ringdown spectroscopy: Application to laser ablated carbon clusters," *J. Chem. Phys.* **116**, 6640-6647 (2002).

255. D. Kraus, V.E. Bondybey, and R.J. Saykally, "Cavity-Ringdown Spectroscopy Studies of the $B^2\Sigma^+ \leftarrow X^2\Sigma^+$ System of AlO," *ChemPhysChem* **4**, 364-366 (2002).

256. N. Goldman, R.S. Fellers, M.G. Brown, L.B. Braly, C.J. Keoshian, C. Leforestier, and R.J. Saykally, "Spectroscopic Determination of the Water Dimer Intermolecular Potential Energy Surface," *J. Chem. Phys.* **116**, 10148 (2002).

257. J.C. Johnson, H. Yan, R.D. Schaller, P.B. Petersen, P. Yang, and R.J. Saykally, "Near-Field Imaging of Nonlinear Optical Mixing in Single Zinc Oxide Nanowires," *Nano Lett.* **2**, 279-283 (2002).

258.* R.D. Schaller, J.C. Johnson, K.R. Wilson, L.F. Lee, L.H. Haber, and R.J. Saykally, "Nonlinear Chemical Imaging Nanomicroscopy: From Second and Third Harmonic Generation to Multiplex (Broad-Bandwidth) Sum Frequency Generation Near-Field Scanning Optical Microscopy," *J. Phys. Chem. B* **106**, 5143-5154 (2002).

***Invited Cover Article.**

259. P. Yang, H. Yan, S. Mao, R. Russo, J. Johnson, R. Saykally, N. Morris, J. Pham, R. He, and H.-J. Choi, "Controlled growth of ZnO nanowires and their optical properties," *Adv. Funct. Mater.* **12**, 323-331 (2002).

260. R.N. Casaes and R.J. Saykally, "Spectroscopy (CRLAS)," *The McGraw-Hill 2002 Yearbook of Science & Technology*, Mark D. Licker, editor, pp. 331-333 (2001).

261. R.D. Schaller, J.C. Johnson, K.R. Wilson, L.F. Lee, L.H. Haber, and R.J. Saykally, "Characterization of biological structures with nonlinear chemical imaging nanomicroscopy," *Proceedings of the SPIE Conferences, Photonics West 2002,* Proc. SPIE Vol. **4633**, p. 62-68, Commercial and Biomedical Applications of Ultrafast and Free-

Electron Lasers, Glenn S. Edwards; Joseph Neev; Andreas Ostendorf; John C. Sutherland; Eds. (2002).

262. A.J. Huneycutt, R.J. Stickland, F. Hellberg, and R.J. Saykally, "Characterization of gas-phase HCl-H_2O clusters using pulsed infrared cavity ringdown spectroscopy," *Proceedings of the SPIE Conferences, Photonics West 2002,* Proc. SPIE Vol. **4634**, p. 70-77, Methods for Ultrasensitive Detection II, Charles W. Wilkerson; Ed. (2002).

263. R.D. Schaller, J. Ziegelbauer, L.F. Lee, L.H. Haber, and R.J. Saykally, "Chemically Selective Imaging of Subcellular Structure in Human Hepatocytes with Coherent Anti-Stokes Raman Scattering (CARS) Near-field Scanning Optical Microscopy (NSOM)," *J. Phys. Chem. B* **106**, 8489-8492 (2002).

264. J.C. Johnson, H.-J. Choi, K.P. Knutsen, R.D. Schaller, P. Yang, and R.J. Saykally, "Single Gallium Nitride Nanowire Lasers," *Nature Materials* **1**(2), 106-110 (2002).

265. R.D. Schaller, L.F. Lee, J.C. Johnson, L.H. Haber, J. Vieceli, H. Benjamin, T.-Q. Nguyen, B.J. Schwartz, and R.J. Saykally, "The Nature of Interchain Excitations in Conjugated Polymers: Spatially-Varying Solvatochromism of MEH-PPV Films Studied by Near-field Scanning Optical Microscopy (NSOM)," *J. Phys. Chem. B* **106**, 9496-9506 (2002).

266. R.D. Schaller, P.T. Snee, J.C. Johnson, L.F. Lee, K.R. Wilson, L.H. Haber, R.J. Saykally, T.-Q. Nguyen, and B.J. Schwartz, "Nanoscopic interchain aggregate domain formation in conjugated polymer films studied by third harmonic generation near-field scanning optical microscopy," *J. Chem. Phys.* **117**, 6688-6698 (2002).

267.**K.R. Wilson, R.D. Schaller, B.S. Rude, T. Catalano, D.T. Co, J.D. Bozek, and R.J. Saykally, "Surface relaxation in liquid water and methanol studied by x-ray absorption spectroscopy," *J. Chem. Phys.* **117**, 7738-7744 (2002).

****Featured by Nature in "News and Views," and by Science as "Editors' Choice."**

268. C. Leforestier, R.S. Fellers, and R.J. Saykally, "Determination of a flexible (12D) water dimer potential via direct inversion of spectroscopic data," *J. Chem. Phys.* **117**, 8710 (2002).

269. F.N. Keutsch, David J. Wales, and R.J. Saykally, "Bifurcation tunneling dynamics in the water trimer," *J. Chem. Phys.* **117**, 8823 (2002).

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