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<p>Molecular beam scattering techniques have firmly established themselves among the major tools for studying the kinetics and dynamics of gas-surface interactions. They have also proven themselves to be of great use in materials synthesis, most notably being used for the molecular beam epitaxial (MBE) growth of semiconductor substrates and superlattices. During the past few years our research group has been very active in developing new and quite general molecular beam techniques for studying the kinetic mechanisms of surface chemical reactions. We have, in particular, focussed much of our attention on extending traditional molecular beam measurements to allow us to routinely explore <i>coverage dependent</i> kinetic mechanisms under essentially <i>linearized</i> conditions. These efforts have been quite successful. Our <i>three</i> molecular beam scattering arrangement is unique in the world, and significantly expands the range and power of modulated beam reactive scattering for studying complex kinetics at surfaces. The experimental methodology we have developed utilizes two continuous, independently adjustable beams to establish a desired steady state surface concentration, while a weaker modulated third beam</p> <p style="text-align: right;">(Continued on reverse side)</p>					
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Abstract (continued)

induces small concentration perturbations around the selected steady state. This linearized approach permits the coupled differential equations which represent the overall surface reaction mechanism to be solved perturbatively, yielding quantitative information about the various kinetic steps which comprise overall reaction mechanisms. Other advantages include the exploration of the global behavior of reactions as a function of surface coverage and temperature, the determination of coverage dependent rate constants, and the isolation of individual elementary steps from complex reaction mechanisms. Another major innovation was the successful development of time-resolved helium reflectivity as a probe of isotheric surface kinetics. Experimental results for a variety of systems are given in this report. The experimental techniques and methodologies pioneered in this program will, in the future, be directly applicable to the chemistry of advanced materials growth, including mechanistic studies, in-situ structural analysis during film deposition, and the actual synthesis of technologically useful electronic and optical materials.

**Gas-Surface Interactions**  
**N-00014-89-J-1061**

**Final Technical Report**


**Submitted by: Steven J. Sibener**

**The James Franck Institute and  
 Department of Chemistry  
 The University of Chicago  
 5640 South Ellis Avenue  
 Chicago, Illinois 60637**

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## **Abstract**

Molecular beam scattering techniques have firmly established themselves among the major tools for studying the kinetics and dynamics of gas-surface interactions. They have also proven themselves to be of great use in materials synthesis, most notably being used for the molecular beam epitaxial (MBE) growth of semiconductor substrates and superlattices. During the past few years our research group has been very active in developing new and quite general molecular beam techniques for studying the kinetic mechanisms of surface chemical reactions. We have in particular focussed much of our attention on extending traditional molecular beam measurements to allow us to routinely explore *coverage dependent* kinetic mechanisms under essentially *linearized* conditions. These efforts have been quite successful. Our *three* molecular beam scattering arrangement is unique in the world, and significantly expands the range and power of modulated beam reactive scattering for studying complex kinetics at surfaces. The experimental methodology we have developed utilizes two continuous, independently adjustable beams to establish a desired steady state surface concentration, while a weaker modulated third beam induces small concentration perturbations around the selected steady state. This linearized approach permits the coupled differential equations which represent the overall surface reaction mechanism to be solved perturbatively, yielding quantitative information about the various kinetic steps which comprise overall reaction mechanisms. Other advantages include the exploration of the global behavior of reactions as a function of surface coverage and temperature, the determination of coverage dependent rate constants, and the isolation of individual elementary steps from complex reaction mechanisms. Another major innovation was the successful development of time-resolved helium reflectivity as a probe of isosteric surface kinetics. Experimental results for a variety of systems are given in this report. The experimental techniques and methodologies pioneered in this program will, in the future, be directly applicable to the chemistry of advanced materials growth, including mechanistic studies, in-situ structural analysis during film deposition, and the actual synthesis of technologically useful electronic and optical materials.

## **Personnel**

Our research program has been quite successful in attracting and educating some of the best young scientific talent in the country, including undergraduates, graduate students, and postdoctoral fellows. Our research group currently consists of seven graduate students, one postdoctoral fellow, and two outstanding undergraduates. Listed in order of seniority, these include: Dr. Thomas Curtiss, Suzanne King, Glenn Tisdale, Kevin Peterlinz, Licheng Niu, Jennifer Colonell, Michael Stirniman, Errol Sanchez, Jason Fleischer, and Sarah O'Conner.

In recent years graduates of our research group have won noteworthy awards for their ONR sponsored thesis work, including the Nottingham Prize at the Physical Electronics Conference (K.D. Gibson), the Norton Prize for excellence in chemistry research (D. Padowitz), and Albert J. Cross Memorial Prize of the U of C chemistry department (D. Padowitz). In addition to the above, note that the PI was awarded the 1988 Marlow Medal of the Royal Society of Chemistry for research primarily sponsored by the ONR. Our ONR supported program has continued to attract students of unusual ability, currently including Dr. Thomas Curtiss who is the James Franck Fellow in Experimental Physical Chemistry (one such fellowship is given every two years in our institute) and Jennifer Colonell (who is both an AT&T Fellow and a McCormick Fellow).

**Recent alumni (\* alumni who have worked in part on ONR sponsored projects).**

**Graduate Students:**

Daniel Koleske (now at IBM Yorktown Heights)  
 \*David Padowitz (now at Berkeley)  
 \*Warren Menezes (now at Argonne Nat. Lab)  
 \*Barbara Gans (now at Naval Res. Lab)  
 \*Kevin Gibson (AT&T Bell Laboratories)  
 \*Chien-fan Yu (now at IBM Fishkill - perm. staff)  
 Yaw-Wen Yang (U. of Washington, Seattle)

**Other Graduate Students** (doctoral work done on theoretical problems generated by our DoD funded activities):

Peter Knipp (now at Naval Res. Lab, PhD with U. Fano)  
 \*Birgitta Whaley (now at Berkeley - faculty, PhD with J. Light)

**Postdoctoral Fellows:**

\*Wesley Natze (now at IBM Fishkill - perm. staff)  
 \*Larry Brown (now at Texas A&M - faculty)  
 Jeong-Sook Ha (now at Electronics Res. Institute, Taejon, S. Korea)

**Undergraduate Research Students:**

Jeanette Sperhac (graduate student-Univ. of Colorado, Boulder)  
 Sei Lee (teaching science in high school-Mississippi)  
 \*Joe Zwanziger (now at Indiana Univ., Bloomington - faculty)  
 \*Jesus Melendez (working in Phoenix, Az)  
 \*Scott Silence (just finishing at MIT-postdoc at IBM, Almaden)  
 \*Mark Kramer (MD, U. of Chicago)  
 \*Eriko Yagi (working in SF, CA)

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To conclude this section, we wish to also emphasize that we have been quite successful in attracting qualified women and minorities to our program (see above). At the present time three of our group members are women who are citizens of the US. The PI fully recognizes that the future vitality of the American science enterprise will depend on the successful involvement of women and under-represented minorities at all levels of training.

## **Research Accomplishments**

This section briefly describes some of the accomplishments that were achieved under the recently expired ONR grant N00014-89-J-1061. The reader is referred to the 13 papers that are listed in the Publications section of this proposal for further details.

### **Molecular Beam Studies of Surface Reaction Kinetics**

Molecular beam scattering techniques have firmly established themselves among the major tools for studying the kinetics and dynamics of gas-surface interactions. Modulated molecular beam relaxation spectrometry (MBRS), a descendent of Eigen's pioneering work on chemical relaxation, extracts kinetic information by analyzing product evolution in response to a time varying reactant beam flux. Relaxation techniques based on this principle are now widely used in reactive scattering to study heterogeneous chemical reactions. By independently controlling incident gas flux densities, angles, velocities, and internal states, researchers have been able to determine how the dynamical parameters of the incident gas affect molecular adsorption or dissociation on a surface. These experiments provide the basis for comparison with theoretical models of these reactions. Reactive scattering experiments, in which one incident reactant beam flux is held constant while the other is modulated, are one of the only ways of measuring unambiguous on-surface reaction rates.

Note, however, that most previous molecular beam experiments were performed in the low coverage regime where interactions between adsorbed species were negligible. This is unfortunate since technologically practical catalytic systems utilize high reactant gas pressures and can thus achieve high coverages during reactions. Furthermore, thin film and materials growth processes by their very nature occur across the entire range of adsorbate coverage. Our measurements circumvent this technical limitation by employing a novel **three molecular beam arrangement**, and are based on the experimental strategy of performing kinetic measurements by observing the relaxation from small density perturbations which we have experimentally introduced around carefully defined steady state reaction conditions. We accomplish this by using two continuous, independently adjustable beams to establish a selected steady state on the surface, while a weaker modulated third beam induces small concentration perturbations around the selected steady state. This is not the only way to linearize an MBRS experiment, but it is simple and direct, retains the advantages of molecular beam sources, and offers great flexibility in experimental design. (The reader is reminded that, in general, chemical reactions at surfaces are not linear. For example, an elementary bimolecular reaction step involves two species and the rate of reaction depends on the product of their concentrations. If both concentrations change with time, the mechanism will be nonlinear. A reaction will also be nonlinear if the rate constants change with concentration. The difficulty here is that it is hard to extract rates from experimental data in the nonlinear regime, and

is also difficult to analyze postulated reaction mechanisms.) It should be emphasized that linearization is important for our purposes since it allows linear transform analysis to be applied to the experimental data, revealing important details about the overall reaction mechanism. Most importantly, linearization allows us to solve the coupled differential equations for a postulated mechanism using either series expansion or perturbation techniques, allowing us to extract the sought after kinetic information, including the isolation of individual elementary steps from complex reaction mechanisms. A simple test to see if linearization has been experimentally realized is to see if the even harmonics vanish in the Fourier transform of the product time evolution waveform when the system is driven by a purely odd chopper function. This limit has now been accomplished for several systems, including the hydrogen recombination, water synthesis, and CO oxidation reactions on Rh(111).

To summarize, we have developed a unique three beam scattering apparatus which is ideally suited for studying heterogeneous reactions under essentially steady state conditions. We have successfully applied this arrangement to a variety of kinetic problems on transition metal surfaces (see project abstracts and publication list which appear later in this report). In addition, we have demonstrated that such growth and kinetics experiments can be carried out while conducting in-situ surface structural analysis via He diffraction. **The methodologies we have developed are very well suited for studying challenging materials growth problems.**

#### **A New Kinetic Response Amplifier for Surface Kinetic Studies: Helium Reflectivity as a Sensitive Probe of Linearized and Isosteric Surface Kinetics**

Our experience with three beam scattering experiments indicated the need to develop an in-situ probe of surface coverage. After some thought, we felt that specular helium reflectivity would be an excellent avenue to explore for monitoring both surface coverage and isosteric kinetics.

It is well established that the specular reflectivity of He from a surface is a very strong function of surface defect density. If one views adsorbates as localized defects, it can be shown that the He reflectivity falls off exponentially with coverage. We can use this phenomenon to quantify adsorbate coverage with great precision during a scattering experiment.

The final step was to realize that the strong exponential attenuation cross-section for He could be used in a time-resolved manner to actually monitor linearized isosteric surface kinetics. The experiment works like this: i) establish adsorbate coverage at a desired level using a continuous molecular beam for a given temperature ii) send in a second and low intensity adsorbate beam to weakly modulate the adsorbate density around the chosen steady-state iii) monitor the He reflectivity from the system, and in particular the change in reflectivity due to the adsorption-

desorption of the modulated adsorbate beam iv) take the log of the resulting waveform and Fourier transform it to extract the desorption kinetics v) repeat the above for different surface temperatures and adsorbate densities to determine the isosteric kinetics. **All of the above has been done-- and it works very well.**

Note that this is only the beginning: the aim is to now start studying reactive systems, and to determine the reaction dynamics, i.e. the energy disposal and angular distributions, as a function of surface coverage. Such measurements will yield the needed details for developing an improved understanding of heterogeneous reactions.

## **Specific Research Projects -- Abstracted Summaries**

### **A Molecular Beam Scattering Investigation of the Oxidation of CO on Rh(111). II. Angular and Velocity Distributions of the CO<sub>2</sub> Product** (L.S. Brown and S.J. Sibener)

Molecular beam and time of flight methods have been used to examine the angular distributions and velocity distributions of the CO<sub>2</sub> product molecules formed in the catalytic oxidation of CO on a Rh(111) single crystal in the surface temperature range 700 - 1000 K. The angular distribution was sharply peaked about the surface normal, and cannot be described by a simple  $\cos^2\theta$  expression. No temperature dependence was observed in the angular distribution over the range of temperatures studied here. Observed velocity distributions were clearly non-Maxwellian and had average translational energies in excess of those expected at the surface temperatures. Furthermore, the average velocity depended strongly on the desorption angle. Molecules desorbing along the surface normal had an average translational energy of ~8 kcal/mol. The average energy decreased with increasing angle, reaching a value of ~4 kcal/mol at an angle of 60°. All of the observed velocity distributions were narrower than Maxwellian distributions with the same average energies. Product velocity distributions did not appear to vary with surface temperature. The observed excess energies are believed to arise from the crossing of the activation barrier to reaction, with a fraction of the reaction energy being carried away from the surface by the product molecules.

### **Sublimation of Nitric Oxide Films: Rotational and Angular Distributions of Desorbing Molecules** (D.F. Padowitz and S. J. Sibener)

NO molecules subliming into vacuum from a condensed NO film at 50 K exhibit cosine angular flux and Boltzmann rotational distribution at the surface temperature. This implies that the sticking probability for incident molecules is independent of angle or rotational energy, at least for levels populated at 50 K. We look at some models for rotational distributions of desorbing molecules, and consider the extent to which desorption can be used as a probe of the surface dynamics of condensed phases. Though our results are simple, they touch on issues fundamental to obtaining microscopic dynamical information for non-equilibrium interfaces.



## **New Modulated Molecular Beam Scattering Methods for Probing Nonlinear and Coverage Dependent Reaction Kinetics at Surfaces**

(D. F. Padowitz, K. A. Peterlinz, and S. J. Sibener)

A new *three* molecular beam arrangement is introduced which expands the range and power of modulated beam reactive scattering for studying complex kinetics at surfaces. This paper presents two types of kinetic measurements which utilize this three beam arrangement. The first measurements use two continuous, independently adjustable molecular beams to establish steady state reaction conditions, while a weaker modulated third beam induces small concentration perturbations around the selected steady state. This technique permits experimental linearization of nonlinear kinetics over a wide range of conditions, allowing us to explore the global behavior of reactions, determine coverage dependent rate constants, and isolate individual elementary steps from complex reaction mechanisms. We illustrate these capabilities with preliminary results for the oxidation of hydrogen to water and for the recombination kinetics of hydrogen on the Rh(111) surface. The second group of measurements use time-resolved specular helium scattering as a sensitive in-situ probe of both adsorbate coverage and coverage dependent surface kinetics. The oxidation of CO on Rh(111) under pseudo-first order conditions is examined with this new kinetic probe.

## **Multiple Source Modulated Molecular Beam Reactive Scattering Applied to Hydrogen Recombination and Oxidation on the Rh(111) Surface**

(D.F. Padowitz and S. J. Sibener)

Surface kinetics which are nonlinear and involve multiple reactants are not amenable to standard modulated molecular beam reactive scattering techniques. To explore these complex reactions, we have developed a new three molecular beam arrangement. Two continuous, independently adjustable beams establish steady state surface concentrations, while a third weaker beam is modulated to induce small concentration perturbations around the selected steady state. This permits experimental linearization of nonlinear kinetics over a wide range of coverages, helping us to evaluate coverage dependent rate constants and to isolate individual elementary steps from complex reaction mechanisms. The technique has been applied to the oxidation of hydrogen to water on the Rh(111) surface. We have demonstrated linearization of the water reaction with isotopic substitution forming HDO. The analysis is illustrated by the simpler example of hydrogen-deuterium recombination. HD shows an activation energy of 20 kcal/mol and preexponential on the order of  $10^{-2} \text{ cm}^2 \text{ s}^{-1}$  for the linearized reaction in the low coverage limit.

## **Kinetics of Hydrogen Oxidation to Water on the Rh(111) Surface Using Multiple Source Modulated Molecular Beam Techniques**

(D. F. Padowitz and S. J. Sibener)

We have examined the kinetics of the oxidation of hydrogen to water on the Rh(111) surface using modulated molecular beam reactive scattering. For reactant pressures below  $10^{-4}$  Torr and temperatures from 450-1250 K we observe serial steps, with apparent activation energies of  $2.5 \pm 1$  and  $10 \pm 1$  kcal/mol. Pseudo-first-order preexponential factors are  $10^5$  and  $10^7 \text{ s}^{-1}$ , respectively, varying slightly with oxygen coverage. Reaction is inhibited by excess oxygen. Maximum water production occurs around 650 K. At lower temperatures the reaction becomes nonlinear. We use a new three-molecular beam arrangement. Two continuous, independently adjustable beams establish steady-state concentrations, while a weaker modulated third beam induces small concentration perturbations around the selected steady state. With this technique we varied surface oxygen coverages, used isotopic substitution in the three beams to produce  $\text{H}_2\text{O}$ ,  $\text{D}_2\text{O}$ , and HDO, and linearized the HDO reaction.

## Coverage Dependent Desorption Kinetics of CO from Rh(111) Using Time-Resolved Specular Helium Scattering

(K. A. Peterlinz, T. J. Curtiss, and S. J. Sibener)

Linearized measurements of the coverage dependent desorption rates of CO from Rh(111) were made with a novel three molecular beam apparatus. To measure these isothermal and essentially isosteric rates we introduce a new *kinetic response amplifier*, namely time-resolved specular helium scattering, which makes use of the large attenuation cross section that CO has for specular helium scattering. The measurements are made by using one intense and continuous CO beam to establish a specific adsorbate coverage while another low intensity and chopped CO beam is used to weakly modulate the adsorbate density around the selected steady state. The transient helium reflectivity waveforms we measure during the modulated CO scattering contain the desired kinetic information, and are typically one to almost two orders of magnitude more sensitive to the desorption kinetics than are the signals arising from direct detection of desorbing CO. Desorption rates are reported for  $0 \leq \theta_{\text{CO}} \leq 0.22$  and  $440 \text{ K} \leq T_{\text{S}} \leq 555 \text{ K}$ . He diffraction measurements revealed that the CO overlayer was disordered for all conditions for which kinetics were measured, and that the sticking coefficient varied with coverage as  $S_0(1-3\theta)$ . At least a second order expansion of the chemical potential in terms of CO coverage was needed to explain these rates. The experimentally determined desorption rates can be fit equally well by placing the coverage dependence in either the pre-exponential factor or in the activation energy:

$$k(\theta, T_{\text{S}}) = 1.33 \times 10^{14} \exp(0.344 \theta + 48.8 \theta^2 - (32.3 \text{ kcal/mol}) / (k_{\text{B}} T_{\text{S}})) \text{ sec}^{-1}$$

$$k(\theta, T_{\text{S}}) = 1.33 \times 10^{14} \exp(-(32.3 - 1.62 \theta - 38.3 \theta^2 \text{ kcal/mol}) / (k_{\text{B}} T_{\text{S}})) \text{ sec}^{-1}$$

The measured He diffraction data, sticking coefficient, specular He scattering attenuation vs. CO coverage, and increase in CO desorption rate with increasing coverage imply nearest neighbor repulsive interactions. The use of time-resolved specular He scattering for studying coverage dependent reactions is also discussed.

## New Molecular Beam Methods for Coverage Dependent Kinetic Measurements Utilizing Time-Resolved Specular He Scattering

(K. A. Peterlinz, T. J. Curtiss, and S. J. Sibener)

New multiple molecular beam scattering techniques are introduced and applied to measure the coverage dependent kinetics of CO desorption from and CO oxidation on Rh(111). Kinetic measurements were performed by establishing the desired steady state reactant coverage with a continuous and relatively intense molecular beam, with concurrent specular helium scattering being used to quantify adsorbate coverage. A second, weak, modulated molecular beam was then used to induce small coverage perturbations around the selected steady state. Linearized kinetics under essentially isosteric conditions were then assessed with *time-resolved* specular helium scattering, which we show to be a remarkably sensitive in-situ kinetic probe. He diffraction was also used to monitor adsorbate overlayer structure under reaction conditions.

## Coverage Dependent Desorption Kinetics of CO from Rh(111): A Theoretical Analysis

(S. H. Payne, H. J. Kreuzer, K. A. Peterlinz, T. J. Curtiss, C. Uebing, and S. J. Sibener)

For a triangular lattice gas with up to third-nearest neighbor interactions between CO molecules adsorbed on Rh(111), we calculate the desorption kinetics assuming quasi-equilibrium throughout the desorption process. These calculations are compared with linearized and essentially isosteric kinetic data that were obtained using a three molecular beam scattering arrangement. The

experimental desorption rates and ordered adsorbate structure data, including phase transition temperatures, are accurately reproduced using transfer matrix calculations. From these calculations we obtain quantitative values for inter-adsorbate interactions extending out to third-nearest neighbor distances. Standard Monte Carlo simulations qualitatively show the correct trends in the coverage dependent rate data, but are quantitatively inadequate for this system since the wrong coverage dependence of the sticking coefficient is implicitly assumed.

### **Support for Instrumentation**

During the past few years the PI has been awarded three DoD-URIP grants which have greatly enhanced the research capabilities of his group. These grants [AFOSR-85-0061, N00014-86-G-0165, and AFOSR-89-0153] have all been fully expended, and were primarily used to (i) construct a new combined molecular beam - electron energy loss spectroscopy facility and (ii) construct a new high energy resolution He scattering apparatus for surface phonon spectroscopy and structural studies. The three-beam (formerly two-beam) gas-surface scattering instrument that is extensively discussed in this proposal also benefitted from this infusion of DoD funds. Some of the funds were also used to procure instrumentation that is currently shared among our various scattering laboratories, such as an excimer laser (Lambda MSC103) which is now playing an essential role in our new laser ablation and materials growth facility. The point is that the DoD has in recent years helped us to establish and update an unusually diverse and unique set of instruments that will be used as part of the proposed research program.

During the past two years the University of Chicago has provided funds, through the Louis Block Fund, for the purchase of a quadrupole mass spectrometer for our molecular beam facility. This UTI Model 100C quadrupole unit (\$11,682) is fully operational. The Louis Block Fund also provided funds for the purchase of the AST-386 PC (\$3,311) which controls the data acquisition electronics for this facility. Finally, the university also provided funds for the renovation of the room which houses our new molecular beam and laser ablation materials growth facility (\$9,600).

### **ONR Sponsored Publications and Presentations: 1988-1991**

#### **Publications**

Listed below are the publications which came out of our ONR sponsored research during the 1988-91 time period. Also included at the top of the list is an article authored by the PI when he was a graduate student which appeared in the 1986 commemorative volume which celebrated forty years of ONR sponsored research.

1. A Crossed Molecular Beams Investigation of the Reactions  $O(^3P) + C_6H_6, C_6D_6$ : Office of Naval Research -- Forty Years of Excellence in Support of Naval Science 1946-1986, Commemorative Volume pp. 327-336 (1986) (S.J. Sibener, R.J. Buss, P. Casavecchia, T. Hirooka, and Y.T. Lee).

2. Inelastic Helium Scattering Studies of Ordered Ar, Kr, and Xe Monolayers Physisorbed on Ag(111): Dispersion Curves, Scattering Cross-Sections, and Excitation Lineshapes, *J. Chem. Phys.* 88, 7862 (1988) (K.D. Gibson and S.J. Sibener).
3. Inelastic Helium Scattering Studies of the Surface Vibrational Spectroscopy and Dynamics of Ordered Ar, Kr, and Xe Multilayers Physisorbed on Ag(111), *J. Chem. Phys.* 88, 7893 (1988) (K.D. Gibson and S.J. Sibener).
4. Elastic Helium Scattering Studies of Ordered Overlayers of Ar, Kr, and Xe Physisorbed on Ag(111), *J. Chem. Phys.* 88, 7911 (1988) (K.D. Gibson, C. Cerjan, J.C. Light, and S.J. Sibener).
5. Ultraviolet Laser Photodesorption of NO from Condensed Films: Translational and Internal Energy Distributions, *J. Chem. Phys.* 88, 7975 (1988) (W.C. Natzle, D. Padowitz, and S.J. Sibener).
6. A Molecular Beam Scattering Investigation of the Oxidation of CO on Rh(111) I. Kinetics and Mechanism, *J. Chem. Phys.* 89, 1163 (1988) (L.S. Brown and S.J. Sibener).
7. A Molecular Beam Scattering Investigation of the Oxidation of CO on Rh(111). II. Angular and Velocity Distributions of the CO<sub>2</sub> Product, *J. Chem. Phys.*, 90, 2807 (1989) (L.S. Brown and S.J. Sibener).
8. Sublimation of Nitric Oxide Films: Rotational and Angular Distributions of Desorbing Molecules, *Surf. Sci.*, 217, 233 (1989) (D.F. Padowitz and S.J. Sibener).
9. New Modulated Molecular Beam Scattering Methods for Probing Nonlinear and Coverage Dependent Reaction Kinetics at Surfaces, *Langmuir*, 7, 2566 (1991) (D.F. Padowitz, K.A. Peterlinz and S.J. Sibener).
10. Multiple Source Modulated Molecular Beam Reactive Scattering Applied to Hydrogen Recombination and Oxidation on the Rh(111) Surface, *J. Vac. Sci. Tech. A*, 9, 2289 (1991) (D.F. Padowitz and S.J. Sibener).
11. Kinetics of Hydrogen Oxidation to Water on the Rh(111) Surface Using Multiple Source Modulated Molecular Beam Techniques, *Surf. Sci.*, 254, 125 (1991) (D.F. Padowitz and S.J. Sibener).
12. Coverage Dependent Desorption Kinetics of CO from Rh(111) Using Time-Resolved Specular Helium Scattering, *J. Chem. Phys.* 95, 6972 (1991) (K.A. Peterlinz, T.J. Curtiss, and S.J. Sibener).
13. American Chemical Society Monograph, Symposium Series No. 482 Chapter 3: "New Molecular Beam Methods for Coverage Dependent Kinetic Measurements Utilizing Time-Resolved Specular He Scattering", (K.A. Peterlinz, T.J. Curtiss, and S.J. Sibener).
14. Coverage Dependent Desorption Kinetics of CO from Rh(111): A Theoretical Analysis, *Surf. Sci.*, 272, 102 (1992) (S.H. Payne, H.J. Kreuzer, K.A. Peterlinz, T.J. Curtiss, C. Uebing, and S.J. Sibener).

## **Invited Presentations by the PI: 1988-1991**

### **1988**

Symposium on Atomic and Surface Physics VI, La Plagne, France  
 University of California at Irvine, Department of Chemistry, Irvine, CA  
 UCLA, Department of Chemistry, Los Angeles, CA  
 University of Pittsburgh, Department of Chemistry, Pittsburgh, PA  
 Universität Erlangen-Nürnberg, 1988 Visiting Scientist and Guest Lecturer  
 Erlangen, Federal Republic of Germany  
 Adriatico Research Conference on the Application of Lasers in Surface Science, International  
 Centre for Theoretical Physics, Trieste, Italy  
 Ontario Laser and Lightwave Research Centre, University of Toronto  
 Toronto, Canada

### **1989**

SPIE OE/LASE '89, Symposium on Photochemistry in Thin Films  
 Los Angeles, California  
 National ACS Meeting (April 1989), Symposium on Diffusion and Reactivity  
 at Surfaces, Dallas, Texas  
 Gordon Research Conference on Molecular Energy Transfer  
 Session Chair and Overview Presentation on Gas-Surface Interactions  
 Wolfboro, New Hampshire  
 Gordon Research Conference on the Dynamics of Gas-Surface Interactions  
 Andover, New Hampshire  
 International Workshop on Surface Dynamics, University of Texas-Austin

### **1990**

Northwestern University, Department of Chemistry, Evanston, Illinois  
 University of California at San Diego, Department of Chemistry  
 San Diego, California  
 Florida State University, Department of Chemistry, Tallahassee, Florida  
 IBM Thomas J. Watson Research Center, Yorktown Heights, New York  
 Fifth Workshop on Interface Phenomena: Fundamental Concepts of  
 Interfacial Chemistry and Physics, Bar Harbor, Maine  
 200<sup>th</sup> National ACS Meeting (August 1990), Symposium on the Dynamics  
 of Gas-Surface Interactions, Washington, D.C.  
 American Vacuum Society Meeting, Fermilab, Naperville, Illinois  
 Symposium on Chemistry at Surfaces, University of CA at Irvine  
 Wayne State University, Department of Chemistry, Frontiers in Chemistry  
 Series, Detroit, Michigan  
 University of Illinois at Urbana, Department of Chemistry, Urbana, Illinois

### **1991**

University of Notre Dame, Department of Chemistry, Notre Dame, Indiana  
 National ACS Meeting (April 1991), Symposium on Surface Science of  
 Catalysis: In Situ-Probes and Reaction Kinetics, Atlanta, Georgia  
 Surface Canada '91, Symposium on Surface Kinetics  
 Trent University, Peterborough, Ontario  
 Reactions in the Space Environment, Northwestern University, Evanston, IL  
 Conference on Molecule-Surface Interactions, Jülich, Germany

**ONR Sponsored Contributed Talks/Posters By Students and Postdocs 1988-92:**

Photoprocesses at Surfaces, North American Chemical Congress, Toronto,

July 1988 (David Padowitz)

International Laser Science Conference ILS-IV, Atlanta

October 1988 (Wesley Natzle and David Padowitz)

Physical Electronics Conference, Seattle WA, June 1989 (David Padowitz)

Stanford University, Dept. of Chem. Engineering, April 1991 (David Padowitz)

Gordon Research Conference on Dynamics of Gas-Surface Interactions,

August 1991 (Kevin Peterlinz)

Chicago Catalysis Club, May 1990 (Kevin Peterlinz)

Illinois Institute of Technology, May 1990 (David Padowitz)

Amoco Research and Development, Student Meeting,

October 1990 (Kevin Peterlinz)

American Vacuum Society, IL Chapter, October 1991 (Kevin Peterlinz)

Richard Bernstein Memorial Symposium, UCLA, April 1991 (Tom Curtiss)

Amoco Research and Development, October 1990, (Tom Curtiss)

XIVth International Symposium on Molecular Beams, Asilomar, June 1992 (Jennifer Colonell)

## **Curriculum Vitae - Steven J. Sibener**

### **Born**

April 3, 1954; Brooklyn, New York

### **Education**

1971-1975 University of Rochester, Rochester, New York.  
Sc.B. in Chemistry awarded with High Distinction, 1975.  
B.A. in Physics awarded with Distinction, 1975.

1975-1979 University of California, Berkeley.  
M.S. in Chemistry, 1977.  
Ph.D. in Chemistry, 1979.  
Research with Professor Yuan T. Lee.

### **Professional Experience**

Eastman Kodak Research Laboratories, Photographic Research Division, Summer 1974: Electrostatic properties of polymers and polymer-metal interfaces.

Eastman Kodak Research Laboratories, Physics Division, Solid State Physics Research Laboratory, Summer 1975: Oxide growth on GaAsP for MOS fabrication.

Bell Laboratories Postdoctoral Fellow, September 1979 - August 1980.  
Research with Dr. M.J. Cardillo involving molecular beam scattering from single crystal surfaces.

The University of Chicago, The James Franck Institute and  
The Department of Chemistry:

Assistant Professor, August 1980 - June 1985.

Associate Professor, July 1985 - June 1989.

Professor of Chemistry, July 1989 - .

### **Honors and Awards**

Marlow Medal of the Faraday Division of the Royal Society of Chemistry, 1988.

IBM Faculty Development Award, 1984-86

Alfred P. Sloan Foundation Research Fellow, 1983-87

Camille and Henry Dreyfus Young Faculty in Chemistry Award, 1980.

Gulf Oil Research Fellow, University of California, Berkeley

American Institute of Chemists Award, University of Rochester

American Chemical Soc. Div. of Colloid and Surface Chemistry

Undergraduate Thesis Competition Honorable Mention:

"The Shape of Liquid Interfaces," 1975.

Regional Scholar for New York City, University of Rochester

### **Associations**

Phi Beta Kappa

American Physical Society

American Chemical Society

Royal Society of Chemistry

Sigma Xi

AAAS

## Curriculum Vitae - Steven J. Sibener

**Invited Lectureships**

Physikalisches Institut der Universität Erlangen-Nürnberg, 1988

**Consulting**

Dow Chemical USA (1982-1985)

Teltech Resource Network (1985- )

Institute for Defense Analyses (1985- )

**Professional Activities**

Vice-Chairman, 1985 Gordon Research Conference on the Dynamics of Gas-Surface Interactions

Member, Defense Science Study Group--Institute for Defense Analyses (1985 - 1988).

Member, Materials Research Laboratory Policy Committee, The University of Chicago (1987 - ).

Chairman, 1987 Gordon Conference on the Dynamics of Gas-Surface Interactions.

Member, International Advisory Committee of the Vibrations at Surfaces V Conference (September 1987).

Member, Board of Trustee's Visiting Committee for the College of Arts and Science, University of Rochester (July 1, 1987 - ).

Member, Council of the University Senate, The University of Chicago (September 1989 - September 1992).

Member, IQEC '90 Program Committee (May 1990).

Member, Physical Electronics Conference Advisory Committee (1991).

Member, Physical Electronics Conference Committee (1991-1994).

Organizer, Symposium on "Surface Chemistry from Reaction Dynamics Through Materials Growth", ACS National Meeting, August 1992, Washington, DC.

**DoD Consulting of the PI**

The PI was a charter member of the Defense Science Study Group of the Institute for Defense Analyses. He is currently a consultant for IDA.