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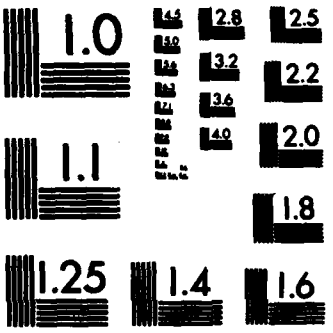

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The title of this research contract describes the initial work done under the contract; after 1980 the research program was extended to the study of the primary decomposition of energetic materials and the dynamics of concerted reactions of organic molecules through cyclic transition states.

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20. Abstract (Continued)

Several reactions of fluorine atoms, fluorine molecules and other halogens were studied using the crossed molecular beams method. The system $F + CH_3I$ allowed the study of the lifetime of and energy randomization in the CH_3IF reaction intermediate before dissociation. A method for synthesizing previously unobserved chemically reactive radicals and measuring their stability was made possible by using a seeded supersonic beam source to promote endothermic reations at higher translational energies. Through the endoergic reaction of F_2 with I_2, ICl and HI the radicals I_2F, ClIF and HIF were synthesized and their IF bond energies measured. In these studies a new mechanism of bimolecular reactions was also elucidated for the reaction $F_2 + I_2 \rightarrow I_2F + F$, and the relative yields of this reaction and the reaction $F_2 + I_2 \rightarrow I + IF + F$ as a function of collision energy was investigated.

Several important techniques were developed during the contract period for the molecular beam experiment. The developments of a high pressure oxygen atomic supersonic plasma beam source allowed a series of mechanistic studies of oxygen atoms with unsaturated hydrocarbons. A molecular beam photoionization apparatus was also constructed in order to have an independent method to verify various reaction products observed in the crossed molecular beams experiments. A supersonic atomic and molecular halogen nozzle beam source was developed to produce high intensity beams of chlorine, bromine and iodine.

The reaction of O atoms with unsaturated and saturated hydrocarbons and halogenated molecules were studied. The primary reaction channels in the reaction of $O(^3P)$ with C_6H_6 and C_6D_6 were identified and the branching ratio between the product channels was investigated as a function of collision energy and isotoptic substitution. The products $CH_3O + H$ were found to be the major ones in the important reaction of $O(^1D) + CH_4$. The study of the reaction $O + ICl$ and $O + CF_3I$ allowed determination of the IO bond strength and modelling of the second reaction as proceeding through a long lived complex.

The studies of the primary photodissociation of polyatomic moleules have been directed toward answering questions related to the primary decomposition of energetic materials and the dynamics of concerted reactions. A combination of the techniques of infrared multiphoton excitation and the molecular beam method has been used to carry out a series of these studies. In particular, the competition between simple bond fission reactions and concerted reactions were studied in detail in the infrared multiphoton dissociation of ethyl vinyl ether and diethyl ether. The primary photodissociation of ozone was studied as it is important both as a test for theoretical models and as a source of $O(^1D)$ atoms in the atmosphere. The photodissociation of the energetic molecules nitromethane was investigated at 266 and at 193 nm. While no significant (<3 percent) dissociation occurred at 266 nm, the 193 excitation led to dissociation to CH_3 and NO_2 with a large fraction of the NO_2 product being electronically excited and highly vibrationally excited. The photodissociation of ketene allowed a determination of the singlet-triplet splitting in methylene.

In order to study the primary dissociation processes of non-volatile compounds a new molecular beam apparatus, equipped with a rotatable beam source and a fixed ultra-high vacuum mass spectrometer, was designed and is now under construction. After completion this machine will be used for another ONR research contract which is essentially the continuation of this contract.

Final Technical Report
Prepared for the

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Arlington, Virginia

by

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CROSSED MOLECULAR BEAM STUDIES OF THE REACTIONS OF OXYGEN AND FLUORINE ATOMS

Period of Contract: April 1, 1975 to September 30, 1983

Contract Number: N00014-75-C-0671

INTRODUCTION

The title of this research contract does not fully represent the contents of our research work carried out under this contract.

We initiated this program by investigating the reactions of fluorine atoms. After the discovery of new and exciting reactions involving fluorine molecules at higher translational energies, we applied this method to the synthetic and energetics studies of fluorine containing radical molecules. In order to make some meaningful comparison, reactions involving other halogen atoms were also carried out by using the crossed molecular beams method.

Much effort was devoted to the development of various techniques for new molecular beams experiments. The successful development of the oxygen atom beam source has been important for a series of mechanistic studies involving oxygen atoms with unsaturated hydrocarbons. In order to probe the content of the oxygen atom beam source, a photoionization molecular beam apparatus was constructed, which was found to be quite useful in the later investigation of the energetics of molecular ions. For the possible production of an $O(^1D)$ beam source by the photodissociation method, we initiated molecular beam photofragmentation translational spectroscopy experiments to study for the dissociation of ozone and other molecules.

Since 1980, with the agreement of our program monitor, the direction of our program has changed to emphasize the decomposition of polyatomic molecules. Especially questions relating to the primary decomposition of energetic materials and the dynamics of concerted reactions in general have

been the objectives. We used the combination of infrared multiphoton excitation and the molecular beam method to carry out this series of studies.

In order to study the primary dissociation processes of a non-volatile compounds, a new molecular beam apparatus, equipped with a rotatable beam source and a fixed ultra-high vacuum mass spectrometer, was designed and is now under construction. After completion this machine will be used for another ONR research contract which is essentially the continuation of this contract.

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TECHNICAL PROGRESS SUMMARY

1) Reaction of Fluorine Atoms, Fluorine Molecules and Other Halogen Atoms.

A) $F + CH_3I \rightarrow IF + CH_3$

Reaction dynamics, the lifetime of reaction intermediate CH_3IF and the extent of energy randomization in the CH_3IF complex before decomposition were investigated in great detail.

B) Stability of Fluorine Containing New Radicals

A high energy F_2 molecular beam source developed under the ONR contract enabled us to develop a new synthetic method for the study of chemically reactive radicals that had not been observed previously.

Through high energy endoergic reactions of F_2 with I_2, ICl and HI, we have successfully synthesized I_2F, ClIF and HIF radicals. From the threshold energies of formation of these compounds IF bond energies are determined to be 33, 31 and 19 kcal/mole for I_2F, ClIF and HIF.

C) New Mechanism of Bimolecular Reactions

In the study of fluorine containing radicals, the stability of I_2F surprised us immensely. We didn't expect that the IF bond strength in this molecule would be as large as 33 kcal/mole, nor that the reaction $I_2 + F_2 \rightarrow I_2F + F$ would proceed at such a low energy (~4 kcal/mole).

It is usually assumed that halogen molecule exchange reactions proceed either through four center bimolecular reactions or atom molecule reactions followed by initial dissociation of diatomic molecules into atoms. The

reaction, such as, $I_2 + F_2 \rightarrow I_2F + F$ had not been speculated in the past. This is mainly due to our lack of knowledge of the nature of chemical bonding and the information on the stability of I_2F radical.

We have investigated collisions between F_2 and I_2 as a function of collision energies. Indeed, the formation of I_2F and the simultaneous generation of F is the reaction channel which proceeds at lowest collision energy. When the kinetic energy is more than 7 kcal/mole $F_2 + I_2 \rightarrow I + IF + F$ channel becomes more important.

D) A Crossed Molecular Beam Study of the $Cl + Br_2 \rightarrow BrCl + Br$ Reaction

We have completed a crossed molecular beam study of the $Cl + Br_2 \rightarrow BrCl + Br$ reaction at several collision energies. Angular distribution as well as velocity distributions of the scattered BrCl product have been measured.

The results of this work and the results of an investigation of this reaction at lower collision energy (~3.0 kcal/mole) seem to indicate that the $Cl + Br_2$ reaction occurs on an attractive energy surface without any appreciable activation energy or barrier. Although the $Cl + Br_2$ interaction seems to be an attractive one, the total reactive cross sections are much smaller than hard sphere values. The sharp recoil energy distribution at the high collision energy, peaking at 14 percent of the total available energy, seems to indicate that the reaction is approaching the spectator stripping model, which predicts a unique recoil translational energy, 11 percent of total available energy at this collision energy.

E) Energy Randomization in the $Cl + C_2H_3Br \rightarrow Br + C_2H_3Cl$ Reaction

When unimolecular processes are studied under single collision conditions, product energy distributions can yield information about the reaction dynamics. In chemiluminescence experiments with the reaction

$$Cl + C_2H_3 Br \rightarrow Br + C_2H_3Cl$$

Durana and McDonald found a product vibrational energy distribution which was inconsistent with a complete randomization of energy in the intermediate complex. On the other hand, Cheung et al. found in crossed molecular beam experiments that the product translational energy distribution for this reaction agreed with the predictions based on a statistical model. This apparent contradiction in product energy distributions led us to study the reaction using crossed supersonic beams with relatively low velocity spreads. The high average translational energy release observed in our experiment shows that this reaction cannot be treated with a purely statistical model.

2) Development of Experimental Methods and Technologies

A) Development of a High Pressure Oxygen Atom Supersonic Plasma Beam Source

A high pressure (supersonic) radio frequency discharge beam source has been developed which is capable of producing a high intensity beam of ground-state oxygen atoms. Impedance matching of the RF to the inductively

coupled plasma, as a function of both gas pressure and composition, allows for routine operation of the beam source with a standing wave ratio of less than 1.05:1. Preliminary results on beam characterization and O - He elastic scattering experiments are reported. In paticular, molecular oxygen dissociation on the order of 80 - 90 percent has been observed in these initial (low-power) studies.

B) Molecular Beam Photoionization Apparatus

In the reaction of oxygen atoms with unsaturated hydrocarbons, it is very common to have several reaction channels taking place simultaneously. In order to have an independent method to verify various reaction products observed in the electron bombardment mass spectrometric detector in a cross molecular beamsexperiment, a molecular beam photoionization apparatus was constructed. This apparatus is equipped with a 1-m vacuum UV monochromator which has been in full operation with a new automatic wave length scanning and data acquisition device. While the oxygen atom beam source was being developed, several experiments were carried out to demonstrate the unique capability of this apparatus.

C) A Supersonic Atomic and Molecular Halogen Nozzle Beam Source

A reliable, resistance heated, nozzle beam source is described which is capable of producing high intensity supersonic atomic and molecular beams of chlorine, bromine, and iodine. The use of a high density graphite nozzle eliminates corrosion and allows for operation up to 2100K. The performance of this source is reported using seeded halogen gas mixtures which extend the accessible kinetic energy region to several eV.

3) Reaction of Oxygen Atoms

A) A Crossed Molecular Beam Investigation of the Reactions $O(^3P)$ + C_6H_6, C_6D_6

A crossed molecular beam investigation of the reactions of $O(^3P)$ + C_6H_6, C_6D_6 has been carried out using a seeded, supersonic, atomic oxygen nozzle beam source. Angular and velocity distributions of reaction produts have been used to identify the major reaction pathways. The initially formed triplet biradical, C_6H_6O (C_6H_6O), either decays by hydrogen (deuterium) elimination or becomes stabilized, most likely by nonradiative transition to the S_0 manifold of ground state phenol. CO elimination was not found to be a major channel. The branching ratio between H(D) atom elimination and stabilization was found to be sensitive to both collision energy and isotopic substitution.

B) Observation of CH_3O Product in the Crossed Beam Study of the $O(^1D)$ + CH_4 Reaction.

The reaction of $O(^1D)$ and CH_4 is understood to proceed along two distinct pathways: a) by insertion of $O(^1D_2)$ into the C-H bond to form "hot" methanol, which fragments in the absence of stabilizing collisions; and b) by abstraction of H atoms to form OH and CH_3 radicals. Uncertainty remains as to how the "hot" methanol decomposes. It is suggested that in addition to forming CH_3 and OH by breaking the C-O bond, the other important channel is the elimination of H_2 forming H_2CO. In this crossed molecular beams study, it is shown that formation of H_2 + H_2CO is in fact negligible in comparison with the more important channel, CH_3O + H.

C) The Crossed Beam Reaction of Atomic Oxygen with ICl and CF_3I

An RF-discharge, supersonic oxygen atom beam source has been used to study the reactions of O + ICl and CF_3I. The IO bond strength determined from the product flux distribution in the ICl reaction, is 55.0 ± 2.0 kcal mol^{-1}, in modest agreement with an earlier measurement. The product from the CF_3I reaction differs in angular and velocity distribution from that of a previous study, and is found to agree well with statistical calculations using a long-lived complex model.

4) Primary Photodissociation of Polyatomic Molecules

A) Ozone Photolysis: A Determination of the Electronic and Vibrational State Distributions of Primary Products

Since photodissociation mechanisms are poorly understood for systems other than diatomics, we chose ozone as a suitable molecule to study. Extensive theoretical and spectroscopic efforts have been made by other workers which renders a base of information complementary to our studies. The photolysis of ozone is important not only from a theoretical view but also as an important source of metastable $O(^1D)$ atoms in the atmosphere. The quantum efficiency for production of $O(^1D)$ has been estimated to be unity for the process

$$O_3(^1A_1) + h\nu(\lambda < 300\ nm) \rightarrow O_3(^1B_2) \rightarrow O_2(^1\Delta_g) + O(^1D).$$

We find, however, that there is an important contribution from previously unseen ground state products. We find at λ=266 nm the quantum efficiency for production of $O(^3P) + O_2(^3\Sigma_g)$ to be 12 percent. This neglected product channel can be significant in quantitative atmospheric modeling calculations.

B) On the Photodissociation of Nitromethane at 266 nm

In a crossed laser-molecular beam study of nitromethane, it was found that the excitation of nitromethane at 266 nm did not yield dissociation products with a quantum yield of >3 percent under collision free conditions. When a small cluster of nitromethane was excited at the same frequency, product was seen only at energies and masses consistent with the rupture of the van der Waals bond by vibrational predissociation of the excited state.

C) Methylene Singlet-Triplet Energy Splitting by Molecular Beam Photodissociation

The singlet-triplet splitting in methylene has been determined from the measurements of fragment velocities from ketene photodissociation at 351 and 308 nm in a molecular beam. The splitting is found to be 8.5 ± 0.8 kcal/mole. This agrees with many experimental results, but not with the value of 19.5 kcal/mole derived from recent photodetachment experiments on CH_2^-.

D) Competing Dissociation Channels in the Infrared Multiphoton Decomposition of Ethyl Vinyl Ether

Infrared multiphoton decomposition of ethyl vinyl ether (EVE) has been investigated by the crossed laser-molecular beam technique. Competition is observed between the two lowest-energy dissociation channels: (1) EVE → $CH_3CHO + C_2H_4$, and (2) EVE → $CH_2CHO + C_2H_5$. Center-of-mass product translational energy distributions were obtained for both dissociation channels. The products of reactions (1) and (2) are formed with mean translational energy of 31 and 5 kcal/mole, respectively. The branching ratio shifts dramatically in favor of the higher energy radical producing channel as the laser intensity and energy fluence are increased, in agreement with the qualitative predictions of statistical unimolecular rate theory.

E) Energy Partitioning to Product Translation in the Infrared Multiphoton Dissociation of Diethyl Ether

The infrared multiphoton decomposition of diethyl ether (DEE) has been investigated by the crossed laser-molecular beam technique. The center-of-mass product translational energy distributions (P(E')) were measured for the two dissociation channels: (1) DEE → $C_2H_5O + C_2H_5$ and (2) DEE → $C_2H_5OH + C_2H_4$. The shape of the P(E') measured for the radical channel (1) is in agreement with the predictions of statistical unimolecular rate theory. The translational energy released in the concerted reaction (2) peaks at 24 kcal/mole; this exceedingly high translational energy release with a relatively narrow distribution results from the recoil

of the products from each other down the exit barrier. Applying statistical unimolecular rate theory, the average energy levels from which DEE dissociates to producs are estimated using the measured P(E') for the radical channel (1).

F) The Photodissociation of Nitromethane at 193 nm

The dissociation of nitromethane following the excitation of the $\pi^* \leftarrow \pi$ transition at 193 nm has been investigated by ~~two independent and comple-~~ mentary techniques, product emission spectroscopy and molecular beam photofragment translational energy spectroscopy. The primary process is shown to be cleavage of the C-N bond to yield CH_3 and NO_2 radicals. The translational energy distribution for this chemical process indicates that there are two distinct mechanisms by which CH_3 and NO_2 radicals are produced. The dominant mechanism releasing a relatively large fraction of the total available energy to translation probably gives NO_2 radicals in a vibrationally excited $^2B_2$ state. When dissociated, other nitroalkanes exhibit the same emission spectrum as CH_3NO_2, suggesting little transfer of energy from the excited NO_2 group to the alkyl group during dissociation for the dominant mechanism. This conclusion is supported by the apparent loss of the slow NO_2 product in the molecular beam studies to unimolecular dissociation to NO + O, which will occur for NO_2 with 72 kcal/mole or more internal energy.

Evidence is presented which suggests that the NO_2 produced via the minor mechanism, which releases a smaller fraction of the available energy to translation, has a large cross section for absorbing an additional photon via a parallel transition and dissociating to NO + O.

List of Publications of ONR Supported Research

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2. Iodine-Fluorine Bond Strength in IIF, ClIF, and HIF, J. J. Valentini, M. J. Coggiola, and Y. T. Lee, J. Am. Chem. Soc. 98, 853 (1976).

3. Molecular Beam Study of F_2 + I_2, M. J. Coggiola, J. J. Valentini, and Y. T. Lee, Int. J. Chem. Kin. 8, 605 (1976).

4. The Question of Energy Randomization in the Decomposition of Chemical Activated C_2H_4F, J. M. Farrar and Y. T. Lee, J. Chem. Phys. 65, 1414 (1976).

5. Crossed Beam Studies of Endoergic Bimolecular Reactions: Production of Stable Trihalogen Radicals, J. J. Valentini, M. J. Coggiola, and Y. T. Lee, Faraday Discussion on Potential Energy Surfaces, University of Sussex, England, 62, (1976).

6. Photoionization with Molecular Beams: I. Autoionization Structure of Nitric Oxide Near the Threshold, C. Y. Ng, B. H. Mahan, and Y. T. Lee, J. Chem. Phys. 65, 1956 (1976).

7. The Binding Energy Between NO and NO^+, C. Y. Ng, P. W. Tiedemann, B. H. Mahan, and Y. T. Lee, J. Chem. Phys. 66, 3985 (1977).

8. Photoionization Studies of the Kr_2 and Ar_2 van der Waals Molecules, C. Y. Ng, D. J. Trevor, B. H. Mahan, and Y. T. Lee, J. Chem. Phys. 66, 446 (1977).

9. Supersonic Atomic and Molecular Halogen Nozzle Beam Source, James J. Valentini, Michael J. Coggiola, and Yuan T. Lee, Rev. Sci. Instrum. 48, 58 (1977).

10. Photoionization Studies of the Diatomic Heteronuclear Rare Gas Molecules XeKr, XeAr, and KrAr, C. Y. Ng, P. W. Tiedemann, B. H. Mahan, and Y. T. Lee, J. Chem. Phys. 66, 5737 (1977).

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12. Molecular Beam Studies of Unimolecular Reactions: Cl, F + C_2H_3Br, Richard J. Buss, Michael J. Coggiola, and Yuan T. Lee, Farad. Disc. Chem. Soc. 67, 162 (1979).

13. Ozone Photolysis: A Determination of the Electronic and Vibrational State Distributions of Primary Products, R. K. Sparks, L. R. Carlson, K. Shobatake, M. L. Kowalczyk, and Y. T. Lee, J. Chem. Phys. 72, 1401 (1980).

14. Development of a Supersonic $O(^3P_J)$, $O(^1D_2)$ Atomic Oxygen Nozzle Beam Source, Steven J. Sibener, Richard J. Buss, Cheuk-Yiu Ng, and Yuan T. Lee, Rev. Sci. Instr. 51, 167 (1980).

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18. Methylene Singlet-Triplet Energy Splitting by Molecular Beam Photodissociation of Ketene, Carl C. Hayden, Daniel M. Neumark, Kosuke Shobatake, Randal K. Sparks, and Yuan T. Lee, J. Chem. Phys. 76, 3607 (1982).

19. Competing Dissociation Channels in the Infrared Multiphoton Decomposition of Ethyl Vinyl Ether, F. Huisken, D. Krajnovich, Z. Zhang, Y. R. Shen, and Y. T. Lee, J. Chem. Phys. 78, 3806 (1983).

20. The Photodissociation of Nitromethane at 193 nm, L. J. Butler, D. Krajnovich, Y. T. Lee, G. Ondrey, and R. Bersohn, J. Chem. Phys. 79, 1708 (1983).

21. Energy Partitioning to Product Translation in the Infrared Multiphoton Dissociation of Diethyl Ether, L. J. Butler, R. J. Buss, R. J. Brudzynski, and Y. T. Lee, J. Phys. Chem. (1983) in press.

Invited Lectures Presented During the Contract Period

1. Y. T. Lee, Molecular Beam Chemistry of Fluorine Containing Radicals, Symposium on Fluroine Containing Radicals, 169th ACS National Meeting, Philadelphia, April 6-11, 1975.

2. Y. T. Lee, Studies in Chemical Dynamics, Annual Conference on Mass Spectrometry and Allied Topics, Houston, Texas, May 1975.

3. Y. T. Lee, Reactive Scattering of F_2 and I_2, IXth International Conference on the Physics of Electronic and Atomic Collisions, Seattle, Washington, July 24-30, 1975.

4. Y. T. Lee, Energetics and Dynamics of Elementary Chemical Reactions, Chemistry Department, California Institute of Technology, Pasadena, California, February 19, 1975.

5. Y. T. Lee, Radical Chemistry by the Molecular Beams Method, Stanford Research Institute, Stanford, California, October 16, 1975.

6. Y. T. Lee, Formation and Decomposition of Radical Molecules, Chemistry Department, University of California, Davis, October 28, 1975.

7. Y. T. Lee, Crossed Molecular Beam Studies on Atomic and Molecular Interactions, Western Spectroscopy Association, 23rd Annual Conference, Asilomar, California, January 28-30, 1976.

8. Y. T. Lee, Recent Studies on Radical Molecules, Univesity of Chicago, Department of Chemistry, Chicago, Illinois, March 1, 1976.

9. Y. T. Lee, Molecular Beam Studies on Reaction Dynamics, TAM-ACS Joint Centennial Symposium on Chemistry, Texas A a M University, College Station, Texas, March 15-16, 1976.

10. Y. T. Lee, Crossed Molecular Beam Chemical Kinetics, Chinese University of Hong Kong, June 9, 1976.

11. Y. T. Lee, Studies of Reaction Dynamics by the Molecular Beams Method, Institute of Nuclear Studies, Taiwan, June 16, 1976.

12. Y. T. Lee, Dynmaics of Chemical Reactions, Department of Chemistry, University of Tokyo, Japan, June 23, 1976.

13. Y. T. Lee, Molecular Beam Isotope Separations, Symposium on Isotope Separation, American Chemical Society Meeting, San Francisco, California, August 30, 1976.

14. Y. T. Lee, Energy Distribution in Products of Bimolecular Reactions, a joint meeting on "Energy Transfer Processes in Chemical Reactions" by the Faraday Division of the Chemical Society, the Societe de Chimie - Physique, the Associatione di Chimica Fisica and the Deutsche Bunsengesellschft, Konigstein, West Germany, September 12-18, 1976.

15. Y. T. Lee, High Energy Collision Between Atoms and Molecules, California Institute of Technology, Pasadena, July 16, 1976.

16. Y. T. Lee, Synthesis and Energetics of Radicals by Crossed Molecular Beams Method, 12th International Symposium on Free Radicals, Laguna Beach, California, January 5-9, 1976.

17. Michael J. Coggiola, Crossed Beam Studies of Endoergic Bimolecular Reactions: ~~Production of Stable Trihalogen Radicals, Faraday~~ Discussion on Potential Energy Surfaces, University of Sussex, England, September 8-10, 1976.

18. Y. T. Lee, Molecular Beam Studies on Dynamics of Infrared Multiphoton Dissociation of Polyatomic Molecules, University of California, Berkeley, Department of Chemistry, February 8, 1977.

19. Y. T. Lee, Dynamics of Multiphoton Dissociation of SF_6 by the Molecular Beam Method, 2nd Winter Colliquium on Laser Induced Chemistry, Park City, Utah, February 13-16, 1977.

20. Y. T. Lee, Molecular Beam Studies on Reaction Dynamics, Project SQUID Annual Meeting, La Jolla, California, March 22-25, 1977.

21. Y. T. Lee, Dynamics of Infrared Multiphoton Dissociation of SF_6 by the Molecular Beam Method, VI International Symposium on Molecular Beams, Noordwijkerhout, Netherlands, April 1977.

22. Y. T. Lee, Molecular Beam Studies on Photoionization of van der Waal's Molecules, N. V. Philip's Gloeilampenfabrieken Research Laboratories, Eindhoven, The Netherlands, April 17, 1977.

23. Y. T. Lee, Photodissociation and Photoionization by the Molecular Beams Method, Fakultat f. Physik der Universitat, Bielefeld, West Germany, May 2, 1977.

24. Y. T. Lee, Molecular Beam Studies on Multiphoton Dissociation of Polyatomic Molecules, Hahn-Meitner-Institut, West Berlin, West Germany, May 4, 1977.

25. Y. T. Lee, Recent Studies on Interaction of Photons with Molecules by the Molecular Beams Method, Max-Planck-Institute fur Stromungsforschung, Gottingen, West Germany, May 6, 1977.

26. Y. T. Lee, Dynamics of Multiphoton Dissociation of Polyatomic Molecules, Max-Planck Institut, Abt. Laser Forschung, Garching, West Germany, May 10, 1977.

27. Y. T. Lee, Photoionization and IR Multiphoton Dissociation of Molecules by the Molecular Beam Method, Naval Research Laboratory, Washington, D.C. May 13, 1977.

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