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CROSSED MOLECULAR BEAM STUDY OF THE REACTIONS OF OXYGEN AND FLU--ETC(U)

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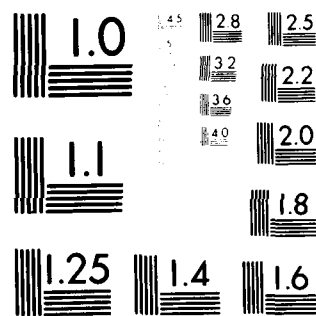
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Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

University of California
Berkeley, California 947202a. REPORT SECURITY CLASSIFICATION
No Restriction

2b. GROUP

AD - A084 255

3. REPORT TITLE

Crossed Molecular Beam Study of the Reactions of Oxygen and
Fluorine Atoms.

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Annual Report Jan 79 - Feb 80

5. AUTHOR(S) (First name, middle initial, last name)

Yuan T. Lee

6. REPORT DATE

March 1, 1980

7a. TOTAL NO. OF PAGES

33

7b. NO. OF REFS

29

8a. CONTRACT OR GRANT NO.

N00014-75-C-0671

8b. ORIGINATOR'S REPORT NUMBER(S)

UC-75-C-0671-80

9. PROJECT NO.

c.

d.

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned
this report)

10. DISTRIBUTION STATEMENT

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

ONR - Power Program

13. ABSTRACT

Rapid developments in our study of oxygen reaction chemistry occurred as we succeeded in obtaining an $O(^1D)$ beam source and commenced investigating the dynamics of several important reactions of $O(^3P)$ and $O(^1D)$.

In the reaction of $O(^3P)$ with C_6H_6 and C_6D_6 , we identified two competing channels, one producing a stabilized addition complex and the other forming radical products $C_6H_5O + H$. Studies of the effects of collision energy and of deuteration were used to clarify the reaction mechanism.

The reaction of $O(^3P)$ with another aromatic hydrocarbon toluene, results in competition between two substitution channels, loss of H atom and loss of CH_3 . In contrast to the $O + C_6H_6$ reaction, no stabilized oxygen-toluene adduct was observed.

The development of an $O(^1D)$ beam source has enabled us to study several reactions of great interest. A reaction of great theoretical interest, $O(^1D) + H_2 \rightarrow H_2O^* + H + OH$, appears to proceed through an insertion process with product translational energy slightly colder than statistical. In the reaction of $O(^1D) + CH_4$ we have identified the H-atom elimination as a primary channel. This observation is in contrast to earlier interpretations of gas phase studies on this system.

DD FORM 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

80 5 16 005

ADA084255

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14

KEY WORDS

Molecular Beams Chemistry

LINK A

LINK B

LINK C

ROLE

WT

ROLE

WT

ROLE

WT

Annual Summary Report Prepared for

Power Program
Office of Naval Research
Arlington, Virginia

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Soc. Sec. No. 555-68-7196

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

Reporting Period: January 1979 to February 1980

Contract No: N00014-75-C-0671

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The research was sponsored by the Office of
Naval Research (N00014-75-C-0671).

- I. Progress Report (January 1, 1979 to December 31, 1979)
Crossed Molecular Beam Study of the Reactions of Oxygen Atoms
and Fluorine Atoms.

N00014-75-C-0671
Principal Investigator:
Yuan T. Lee

INTRODUCTION

This has been the most fruitful and exciting period, since we started our crossed molecular beam investigation of the reactions of oxygen atoms.

First of all, we have not only improved the $O(^3P)$ beam source, but also succeeded in getting our $O(^1D)$ beam source going. Many reactions of $O(^3P)$ and $O(^1D)$ have been studied by the crossed molecular beams method for the first time. Results on reaction dynamics and mechanisms are found to be quite intriguing. Four systems which will be summarized are listed below.

1. Competitive Decay of the Complex Formed in the Reaction $O(^3P) + C_6H_6, C_6D_6$.
2. The Dynamics of the Reaction $O(^1D) + H_2 \rightarrow H_2O^{\ddagger} \rightarrow OH + H$.
3. Primary Product Identification in the Reaction of Oxygen Atoms with Toluene.
4. Observation of CH_3O Product in the Crossed Beam Studies of the $O(^1D_2) + CH_4$ Reaction.

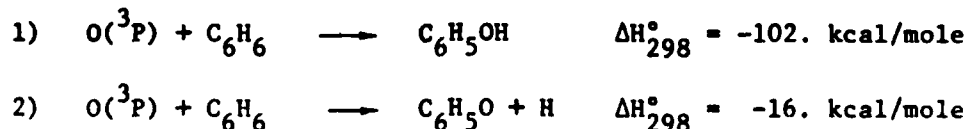
Finally, the complete description of the $O(^3P)$, $O(^1D)$ beam source which will appear in the Review of Scientific Instruments, early 1980, is also attached.

1. Competitive Decay of the Complex Formed in the Reaction $O(^3P) + C_6H_6$ and C_6D_6 .*

R. J. Buss, P. Casavecchia, T. Hirooka, S. J. Sibener and Y. T. Lee

The reactions of oxygen atoms with hydrocarbons are of great interest because they are important in combustion processes, atmospheric chemistry and photochemical air pollution. Although the reaction of $O(^3P)$ with benzene has been studied by a variety of techniques, uncertainty remains concerning the products of the primary reactive event. We have now completed a crossed molecular beam study of this reaction which eliminates the previous difficulties of secondary reactions and has enabled us to identify the primary products unambiguously.

The crossed beam apparatus and supersonic oxygen atom beam have been previously described.¹ About 90 torr of the pure vapor of C_6H_6 or C_6D_6 was expanded from a 0.1 mm nozzle orifice heated to 326°K to prevent condensation. The reactions were studied at two mean collision energies, 2.5 and 6.5 kcal/mole by seeding the oxygen beam in argon and helium respectively. Two reaction channels were observed in this study:



The most intense product signal occurred at masses 65 and 66 which are daughter ions produced by ionizer fragmentation of the parent C_6H_5O and C_6H_5OH molecules. The laboratory angular distributions of product are shown for the higher collision energy in Fig. 1. The

narrow distribution of mass 66 is found to coincide with the calculated distribution proving that it is indeed the result of oxygen attachment, eq. 1. The mass 66 can not be the result of CO elimination from the complex because momentum conservation would greatly broaden the mass 66 distribution. The angular distribution of mass 65 is wider than the centroid distribution as a consequence of the elimination of a hydrogen atom from the complex. The angular distribution of product from the low energy reaction is shown in Fig. 2 with a calculated centroid distribution (dashed line) and a best fit calculation (solid curve), assuming an isotropic angular distribution and the translational energy distribution shown in Fig. 3.

The results of the C_6D_6 reaction are qualitatively the same but the effect of deuteration is to alter the branching ratio of the two channels. In Table I are shown the relative intensities of the detected masses. Because of uncertainties in the fragmentation patterns of the parent species, these intensities do not give actual branching ratios but show only the trends. At both collision energies, deuteration has the effect of increasing the 66/65 and 72/70 ratios, indicating that the formation of phenol is favored by deuteration. Also evident is a strong enhancement of phenol production at the higher collision energy. The reaction of $O(^3P)$ with benzene apparently proceeds through formation of a triplet biradical intermediate. This can decay by one of two routes, nonradiative transition to the S_0 manifold of phenol or decomposition by hydrogen atom loss. We have determined that the complex does not dissociate by elimination of CO as was

previously thought.² While this scheme is the simplest interpretation of our results, further experiments will be necessary to determine whether the 94 product is actually formed by a radiative process, by a ring opening, or if, indeed, it is ground state phenol formed by a nonradiative curve crossing.

Complete description of this work which will appear in the Journal of Chemical Physics, Volume 72 (1980) is attached.

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Rev. Sci. Instr. 40, 1402 (1969); S. J. Sibener, R. J. Buss,
C. Y. Ng, and Y.T. Lee, Rev. Sci. Instr., in press.
2. T. M. Sloane, J. Chem. Phys. 67(5), 2267 (1977).

FIGURE CAPTIONS

- Fig. 1. Angular distributions from the reaction $O(^3P) + C_6H_6$, mean collision energy $E = 6.5$ kcal/mole. The primary reaction products formed were C_6H_5O and C_6H_5OH , which subsequently fragmented during electron bombardment ionization. The solid and dashed lines are drawn through the data for clarity. XBL-794-9157A
- Fig. 2. Angular distributions from the reaction $O(^3P) + C_6H_6$, relative collision energy $E_{rel} = 2.5$ kcal/mole. The dashed line is a calculation of the centroid distribution. The solid line is the calculated distribution described in the text. XBL-798-2454
- Fig. 3. Translational energy distribution of the C_6H_5O product from the reaction $O(^3P) + C_6H_6$, $E_{rel} = 2.5$ kcal/mole. XBL-7910-12122

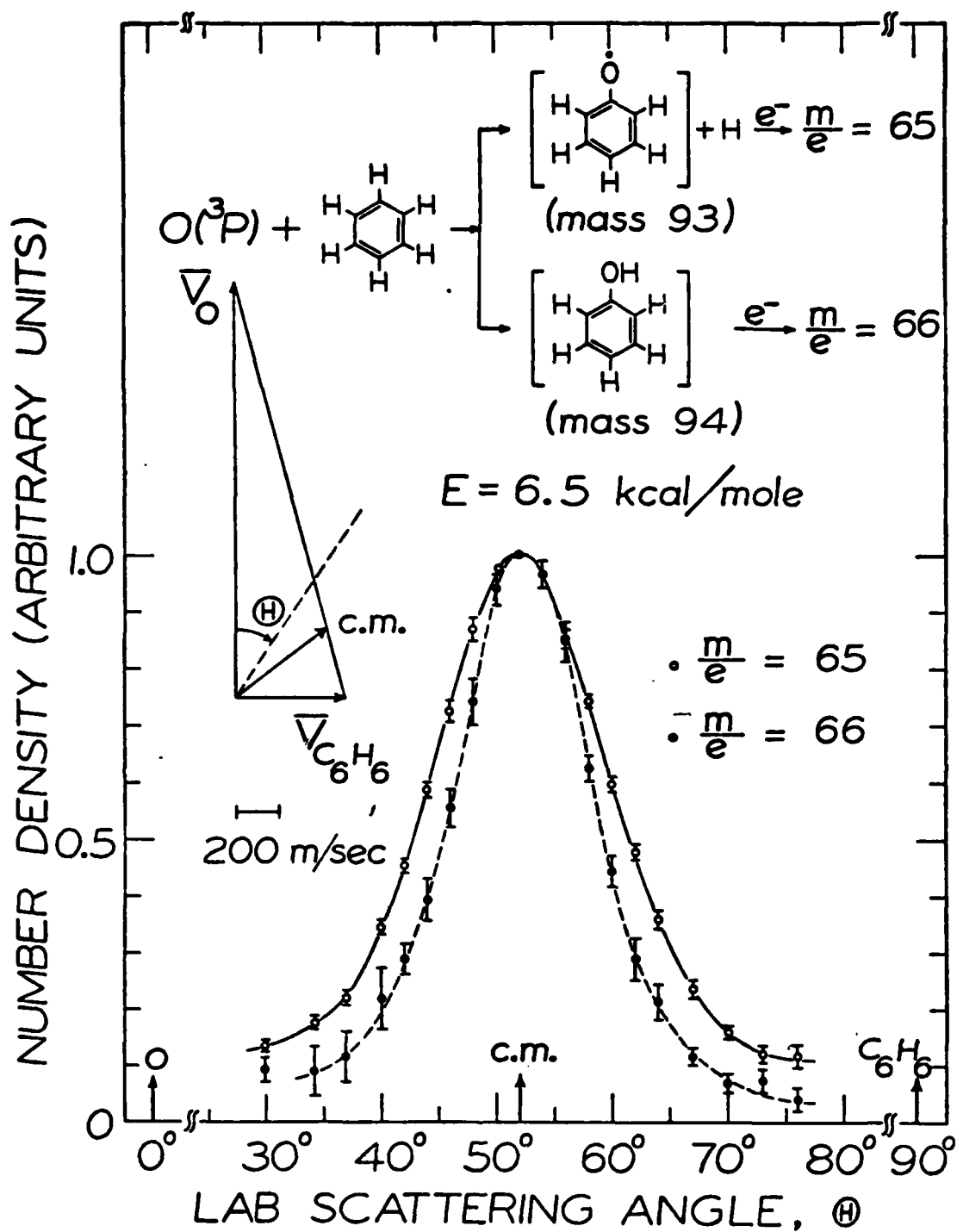


Fig. 1

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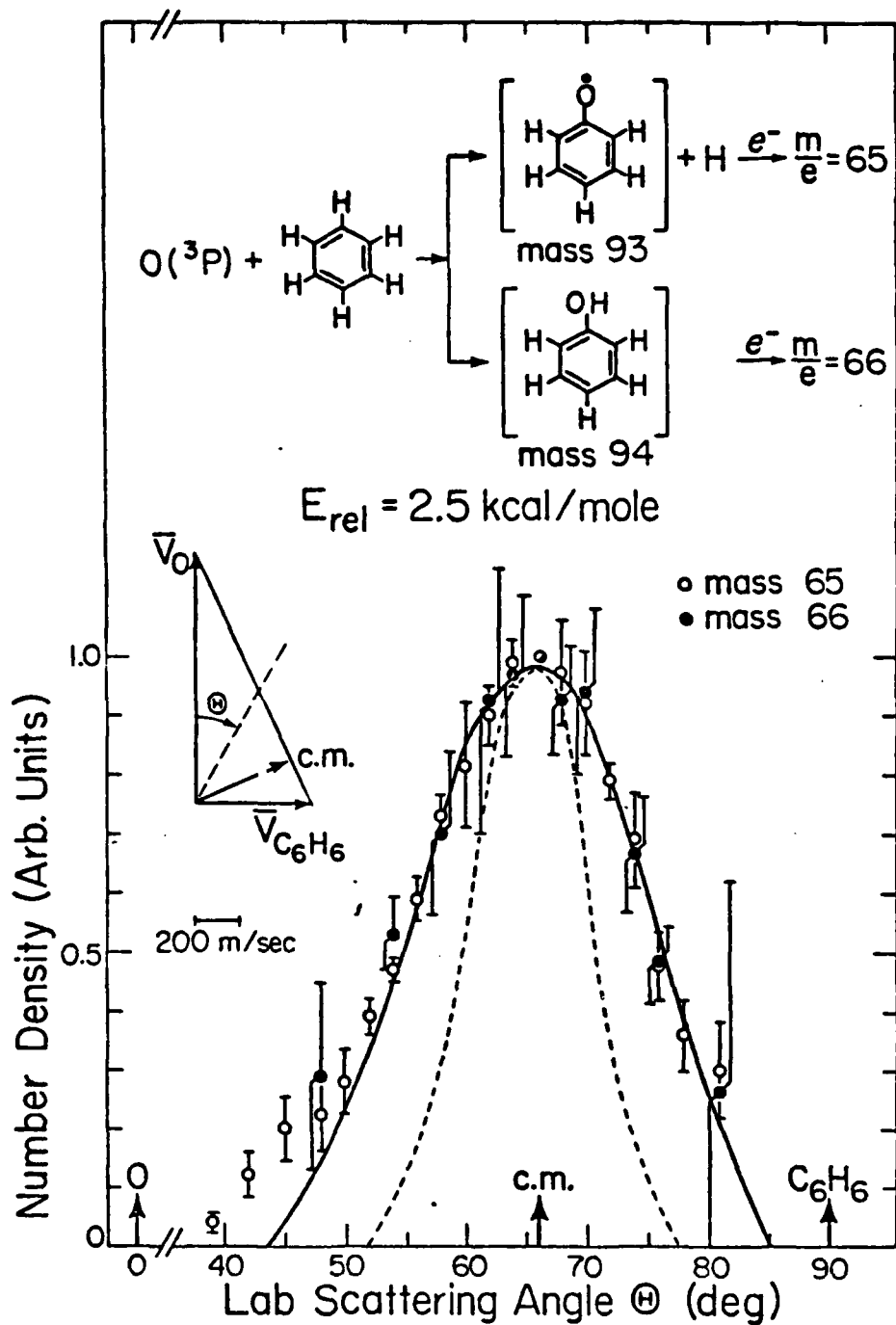


Fig. 2

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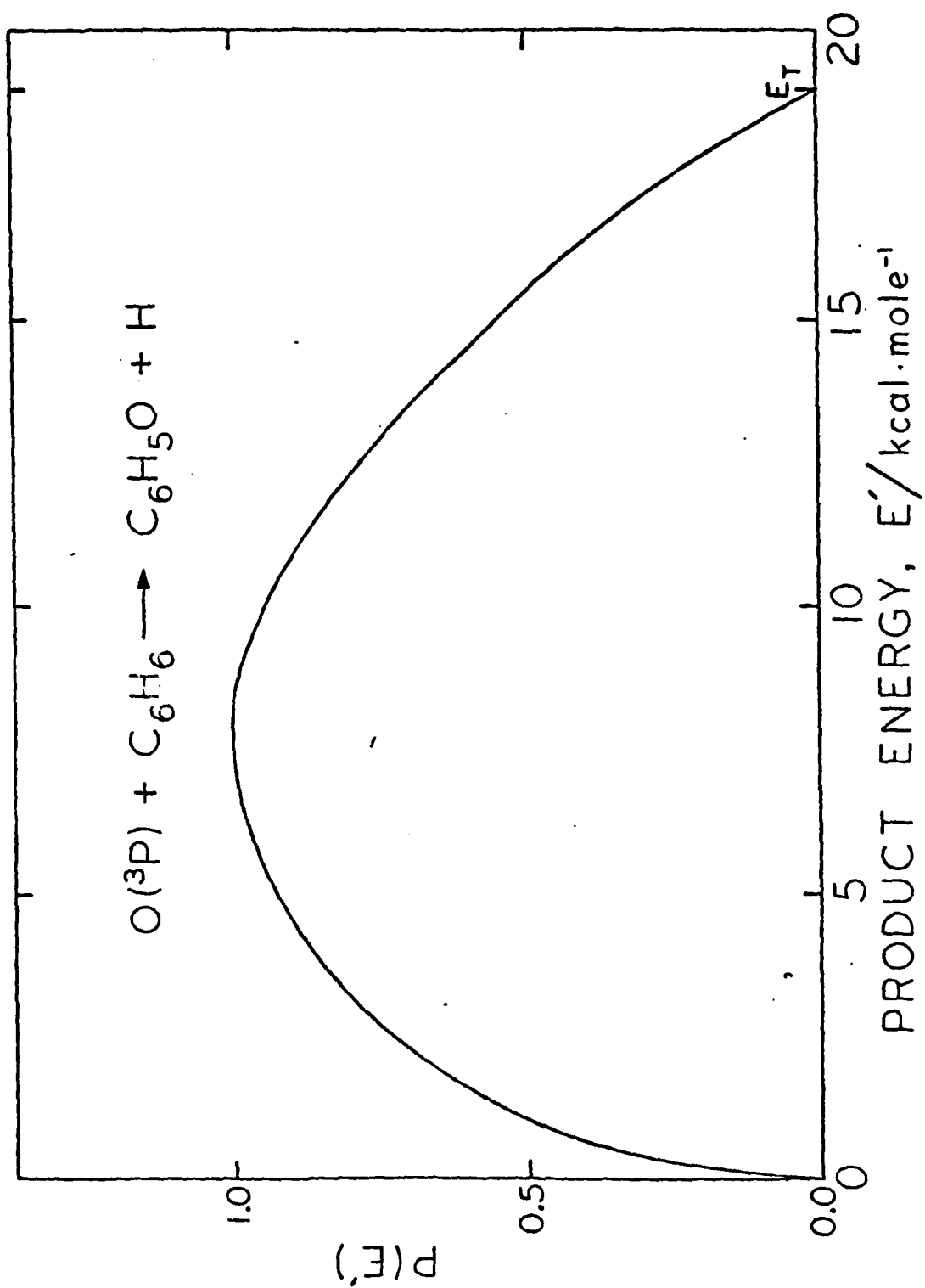


Fig. 3

XBL 7910-12122

2. The Dynamics of the Reaction $O(^1D) + H_2 \rightarrow H_2O + OH + H$.

R. J. Buss, P. Casavecchia, T. Hirooka, S. J. Sibener and Y. T. Lee

The reaction of $O(^1D)$ with H_2 is of particular interest to theoreticians because while it is a sufficiently small system as to be manageable, the theory must accurately account for the participation of a manifold of low lying electronic states. The experimental determination of product state distributions in crossed molecular beams can provide a sensitive test of the dynamical theories. We have used our $O(^1D_2)$ beam source to obtain angular and velocity distributions of OH and OD product from the reaction of $O(^1D)$ with H_2 and D_2 .

We have found that the radio frequency discharge supersonic oxygen atom source¹ can produce a high flux of $O(^1D)$ when helium is used as the seeding gas because helium is ineffective at quenching the excited state oxygen. The hydrogen or deuterium was expanded at a stagnation pressure of 17 atm through a room temperature 30 micron diameter nozzle orifice. The mean collision energy was 2.7 kcal/mole. The cross correlation time of flight method was used to obtain velocity distributions at 17 angles. The angular distribution of OH product is shown in Fig. 1 with a calculated curve, obtained by optimizing the product translational energy $P(E')$ and the center of mass angular distribution $T(\theta)$ to obtain a best fit to the data. The optimum $P(E')$ and $T(\theta)$ (which was found to be symmetric) are shown in Fig. 2. The results for the deuterium reaction, while not yet fully analyzed appear to be qualitatively similar.

The reaction of $O(^1D)$ with H_2 might proceed by insertion of the oxygen into the H_2 bond to form a vibrationally hot water molecule which subsequently dissociates. Alternatively the oxygen might attack collinearly, abstracting an H atom and rebounding. Our product angular distribution is found to be forward-backward symmetric, consistent with the insertion mechanism in which the direction along which the products depart is uncorrelated with the incident direction except for angular momentum constraints. The ab initio potential energy surface (PES) of Howard, McLean and Lester² has no barrier to insertion with a perpendicular approach of the oxygen but indicates, a small barrier 1-3 kcal/mole to collinear approach, and thus gives qualitative agreement with our results. Whitlock, Muckermann and Fisher³ have performed classical trajectory studies on a PES they have obtained using a valence bond method. They have found considerable asymmetry in the product angular distributions, even when only the trajectories which involve insertion of the oxygen are chosen.⁴ However, the product translational energy distribution obtained by them is in quite good agreement with the results of our experiment.

Future studies with improved resolution may help us to derive differential cross sections of the individual product vibrational states for this reaction. Additionally we will extend these studies to include the reaction with HD in which we will look at the competition for formation of OH and OD. These studies provide the theoretician with a sensitive standard with which to compare the accuracy of the PES as well as of the dynamical theories.

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4. J. T. Muckermann, private communication.

FIGURE CAPTIONS

- Fig. 1. Laboratory angular distribution of OH product from the reaction of $O(^1D) + H_2$. The line is a calculated curve using a decoupled angular and energy distribution. XBL-7911-12907
- Fig. 2. A) Center of mass angular distribution of product OH flux. B) Product translational energy distribution obtained for the $O(^1D) + H_2$ reaction. XBL-7912-13560

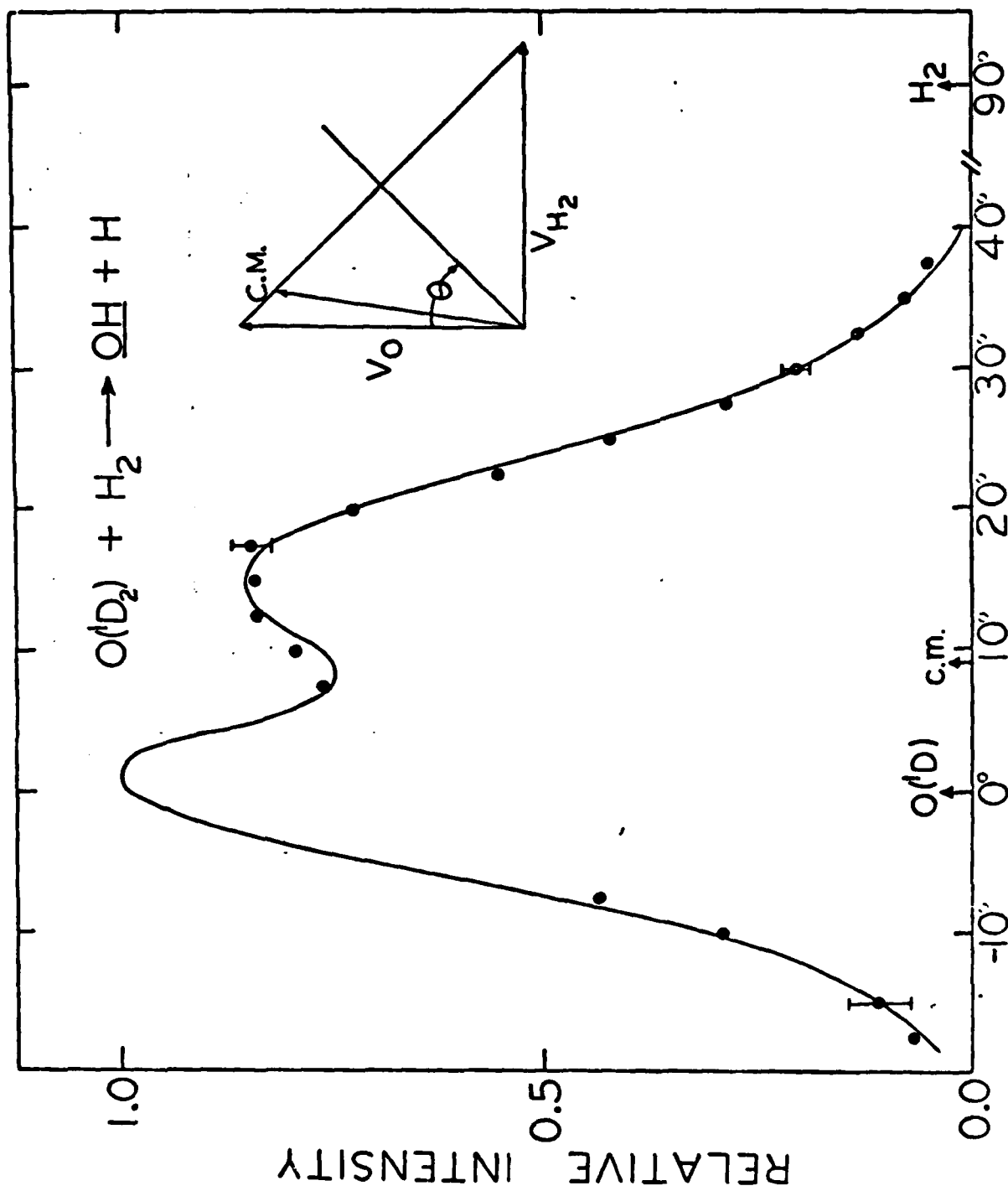


Fig. 1

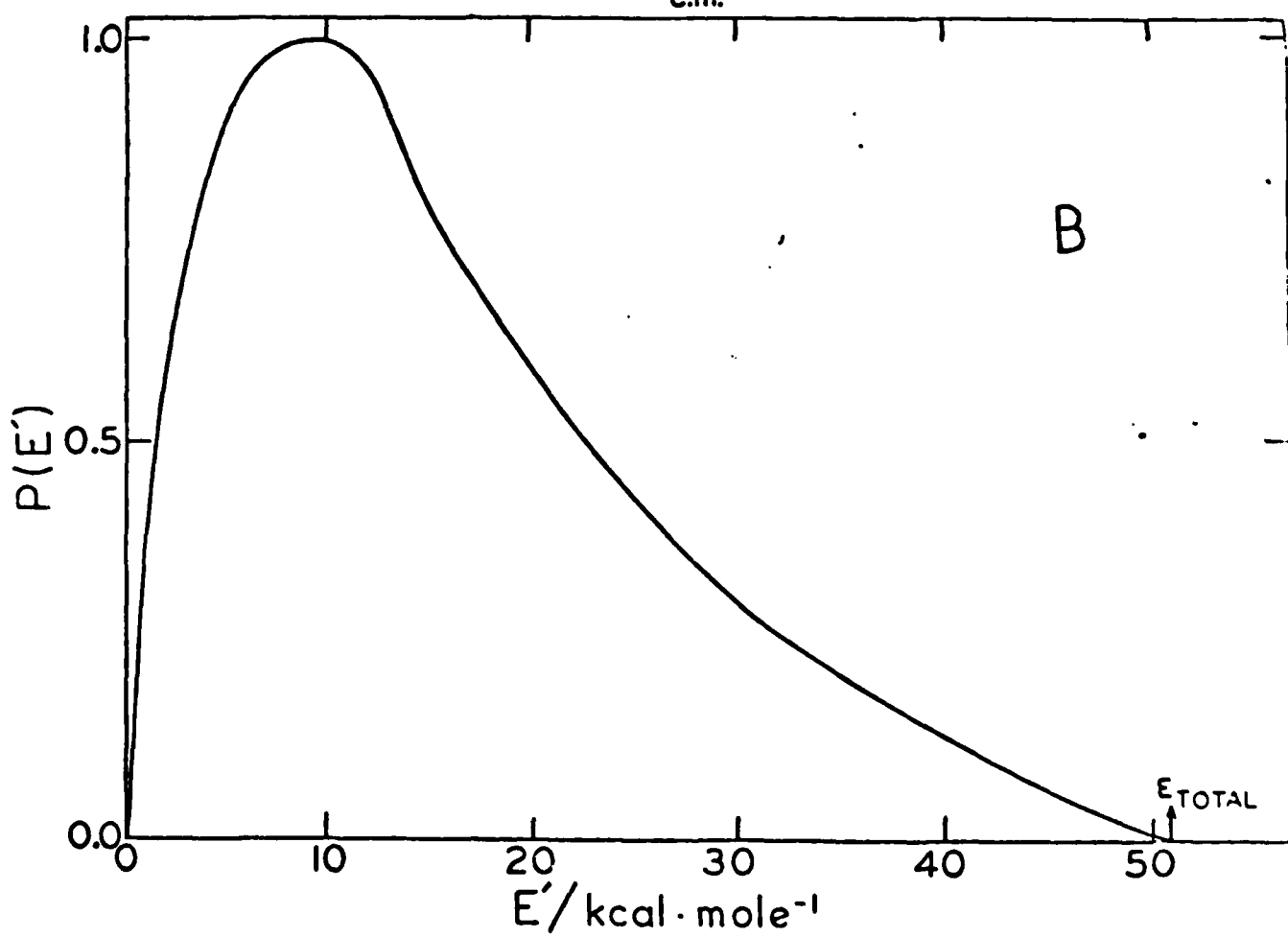
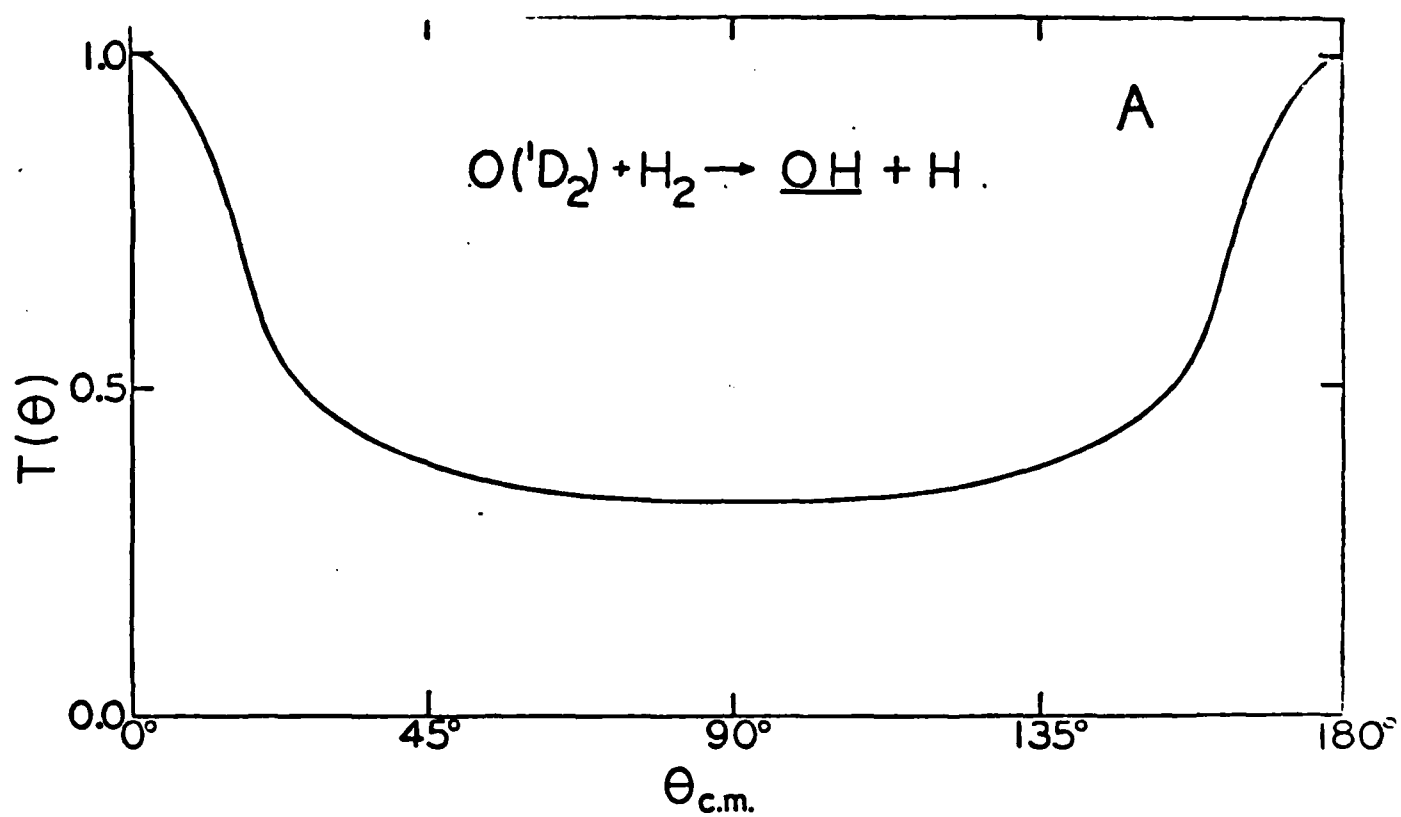


Fig. 2

3. Primary Product Identification in the Reaction of Oxygen Atoms with Toluene.

R. J. Baseman,^a R. J. Buss, P. Casavecchia,^b and Y. T. Lee

We have investigated the reaction of ground state oxygen atoms with toluene under single collision conditions. Previous studies of the rate of this reaction have been reasonably consistent, but there has been uncertainty in the identity of primary products formed.¹⁻⁹ Products reported from bulk phase studies include o-, m-, p-cresol, anisole, benzaldehyde, phenol, methane, ethane, carbon monoxide, benzyl alcohol, and a red-yellow tar. We have observed at least two primary reaction products, C_7H_7O and C_6H_5O , (corresponding to loss of H and loss of CH_3 from an O-toluene adduct) and have failed to observe some previously reported products (i.e., benzaldehyde, cresol, anisole, and benzyl alcohol).

Supersonic beams of $O(^3P)$ atoms produced in a radiofrequency discharge¹⁰ and toluene molecules, from a supersonic expansion of the vapor in equilibrium with liquid toluene at ca. 400°K were crossed at 90° in our crossed beams spectrometer equipped with a rotatable electron bombardment ionizer-electric quadrupole mass spectrometer detector assembly.¹¹ Angular and time of flight (TOF) distributions were measured by monitoring parent and daughter ion intensities. Product was detected as masses 78, 79, 106, 107 and 108.

All angular distributions of these masses were found to be superimposable, and all are wider than the distribution of centroids (Fig. 1). The intensity of mass 108 product is approximately one tenth that of mass 107, about equal to that expected from ¹³C isotopic impurity.

This data then is consistent with mass 107, C_7H_7O being a primary product with mass 78, 79 and 106 being fragments formed in the ionizer. The mass 106 cannot be a primary product of H_2 elimination because this would have resulted in broadening of its angular distribution.

Evidence for C_6H_5O product (CH_3 elimination from C_7H_8O) was found in the mass 65 (C_6H_5O losing CO in the ionizer) spectrum. Angular scans proved fruitless as fragmentation of elastically scattered toluene obscures any reaction features in the mass 65 spectrum. TOF spectra measured with daughter ions of elastically scattered toluene (e.g., mass 91) show two maxima, one due to the elastically scattered secondary beam, the other to main chamber background gas. The mass 65 spectrum shows the same two lines, however with added intensity between the peaks. We believe that this is due to a third line in the mass 65 TOF spectrum, from a mass 65 (C_5H_5) daughter ion of a C_6H_5O reaction product. This line obtained as the difference between normalized (corrected) mass 91 and 65 TOF spectra, is shown in Fig. 2 with the corresponding line from C_7H_7O product. The increased breadth and displacement of the C_6H_5O product associated line relative to that from C_7H_7O product confirms a difference in molecular origin for the two lines.

We have observed H and CH_3 elimination in the reaction of oxygen atoms (3P) and toluene. We have seen no evidence for H_2 elimination. Future considerations of this reaction will allow us to describe the reactive dynamics and product structures more fully.

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- b) Permanent address: Dipartimento di Chimica dell'Universita,
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FIGURE CAPTIONS

- Fig. 1. Angular distribution of mass 107 (C_7H_7O) product formed in the reaction of $O(^3P)$ + toluene. XBL-7912-13563
- Fig. 2. Time of flight spectra of C_7H_7O and C_6H_5O products formed in the reaction of $O(^3P)$ + toluene (C_6H_5O product intensity represented by the C_5H_5 daughter ion). XBL-7910-13564

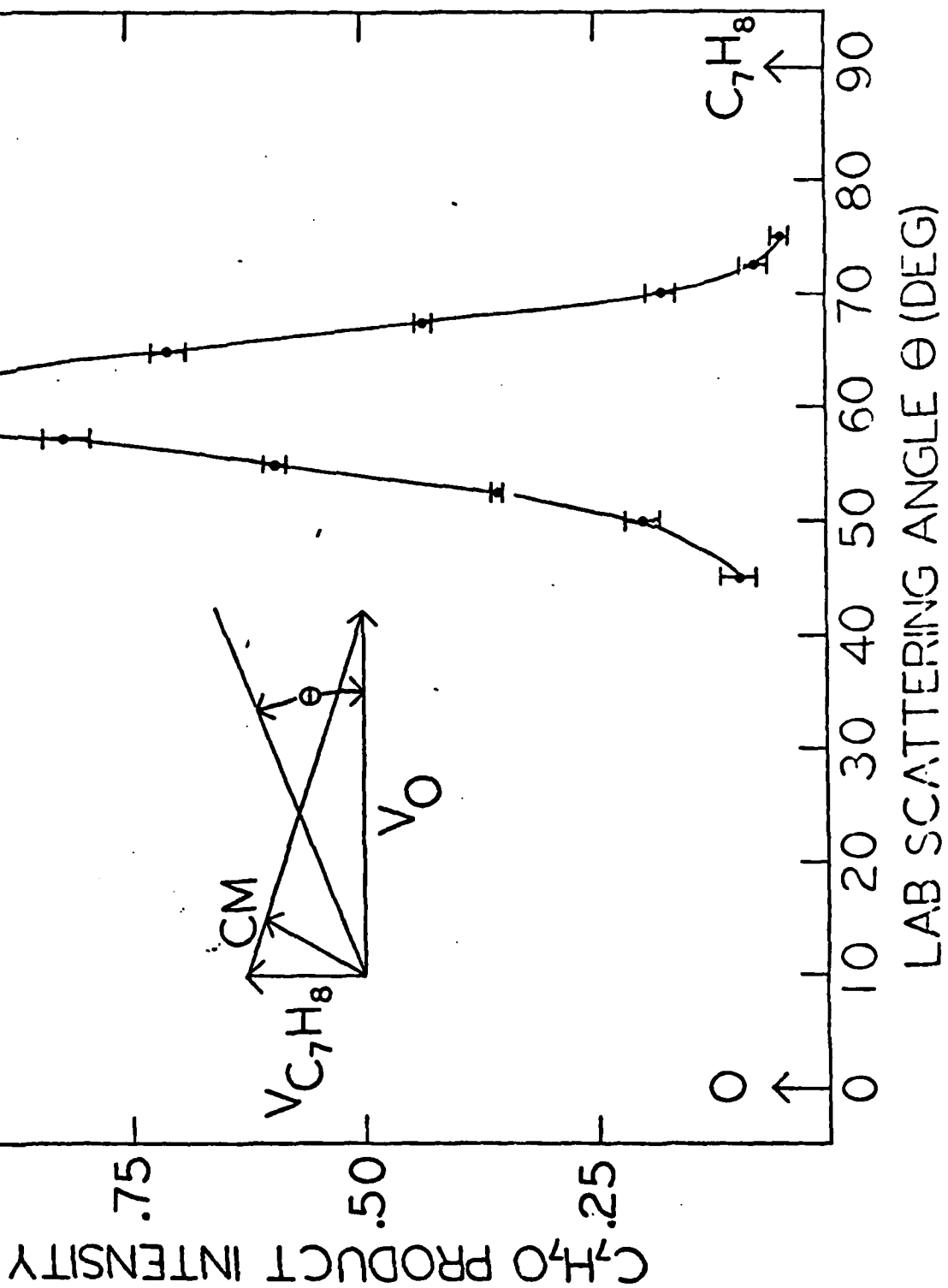
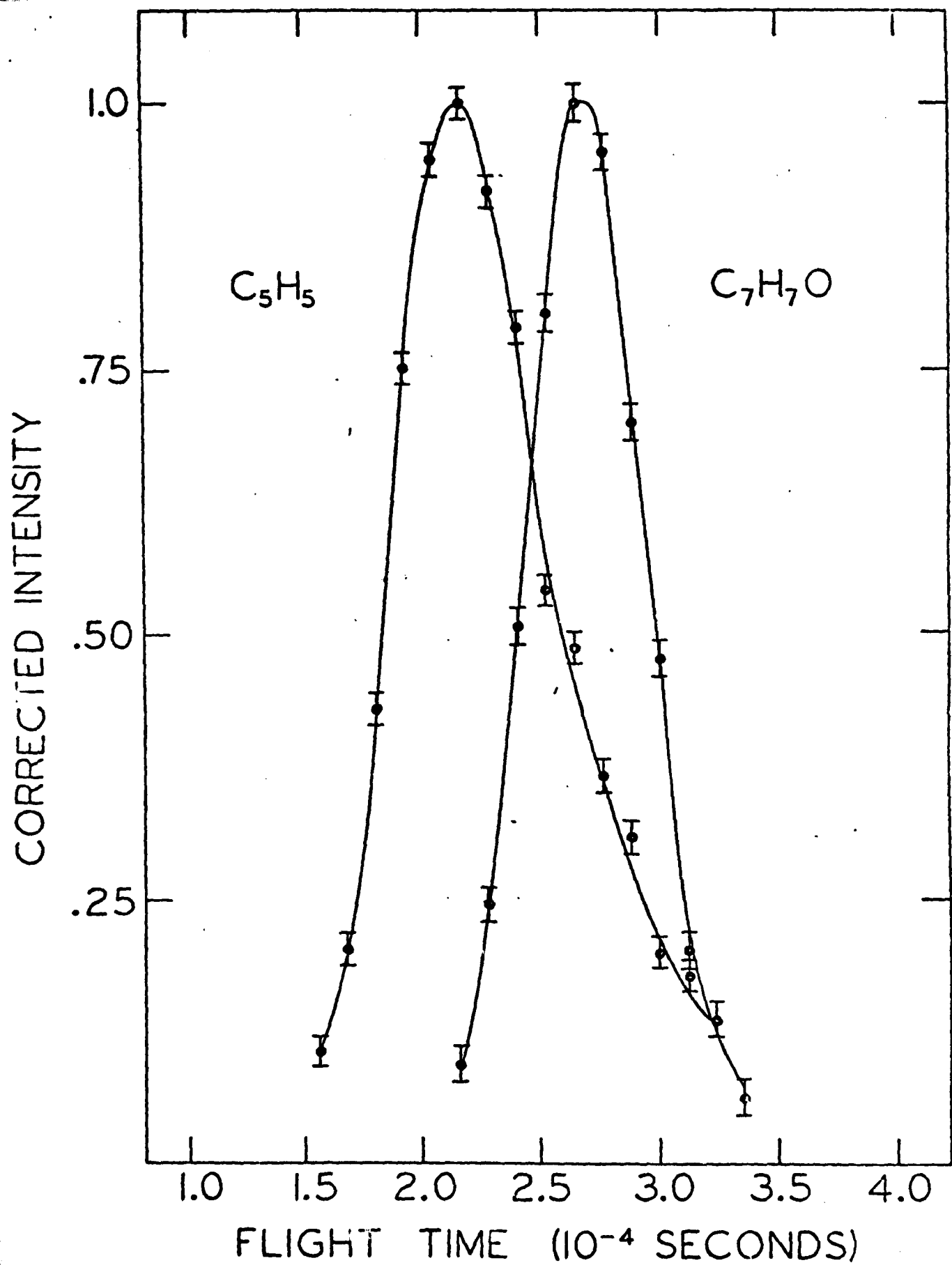


Fig. 1



4. Observation of CH_3O Product in the Crossed Beam Study of the $\text{O}(^1\text{D}_2) + \text{CH}_4$ Reaction.*

P. Casavecchia, R. J. Buss, S. J. Sibener and Y. T. Lee

The reaction of $\text{O}(^1\text{D}_2)$ with methane has been a matter of considerable interest in the past, primarily for its role in stratospheric chemistry.¹ UV photolysis of $\text{N}_2\text{O}-\text{CH}_4$ or O_3-CH_4 mixtures has been used to study this reaction in gas phase²⁻⁶ and also in a liquid argon medium.⁷ At the present time the reaction is understood⁶ to proceed along two distinct pathways: a) by insertion of $\text{O}(^1\text{D}_2)$ into the C-H bond to form "hot" methanol, which fragments in the absence of stabilizing collisions; b) by abstraction of H atoms to form OH and CH_3 radicals. H_2 elimination from "hot" methanol resulting in the formation of formaldehyde has also been observed in liquid Ar and inferred in gas phase as a minor channel. Uncertainty remains whether other precursor radicals, such as CH_3O or CH_2OH , are formed at all. Dimethyl ether has been observed in a low pressure study,³ but there is not direct experimental evidence on the identity of the precursor radicals.

In order to understand the reaction mechanism and to elucidate the dynamics and energetics of the $\text{O}(^1\text{D}_2) + \text{CH}_4$ reaction, we have performed a crossed molecular beam investigation of this reaction using a novel supersonic $\text{O}(^1\text{D}_2)$ beam source developed recently in our laboratory. The seeded $\text{O}(^1\text{D}_2)$ atomic beam is produced from a high pressure, radio frequency discharge nozzle beam source which has been previously described in detail.⁸ Although the beam also contains $\text{O}(^3\text{P})$, undissociated O_2 molecules as well as the He carrier

gas, only $O(^1D_2)$ reacts with CH_4 appreciably at low collision energies.⁴ The $O(^1D_2)$ beam was crossed at 90° with a room temperature supersonic beam of pure CH_4 in a collision chamber maintained at $\sim 1 \times 10^{-7}$ torr. Reaction product angular distributions are measured as a function of in-plane scattering angle by a triply differentially pumped rotatable electron bombardment quadrupole mass spectrometer, kept at $\sim 10^{-11}$ torr in the ionization region.⁹ Product velocity distributions at selected angles are determined by a cross correlation time-of-flight (TOF) technique.¹⁰ Although $C^{13}H_4$ impurity prevents our studying the hydrogen abstraction channel, we observed scattered signal at $m/e = 30, 31$, and 32. Possible origins of $m/e = 32$ are either CH_3OH^+ or O_2 , but since the lifetime of CH_3OH^+ is expected to be too short ($\leq 10^{-12}$ sec)⁶ for it to reach the detector, the $m/e = 32$ signal is believed to be entirely due to elastic scattering of O_2 from CH_4 , as demonstrated by TOF analysis. $m/e = 31$ product was identified with CH_3O (or CH_2OH) radical formation from the chemical reaction. $m/e = 30$ product cannot be identified directly from a mass spectrometric detection, since it can be either formaldehyde (H_2CO) or a fragment of $m/e = 31$ product. But in a crossed molecular beam experiment it is possible to positively identify the origin of $m/e = 30$ from precise measurement of angular and velocity distributions because of the dynamical and energetic constraints imposed on the reaction system. The $m/e = 30$ angular distribution is rather narrow and is peaked at the center of mass and is shown to come from the fragmentation of mass 31 product (CH_3O or CH_2OH) in the ionizer. Since the $m/e = 31$ signal

is strongly contaminated, especially at small angles, by the low mass tail of the intense m/e 32 elastic signal, a reliable angular distribution of m/e 31 is difficult to obtain. However, in the TOF data the reactive m/e 31 signal is separated from that due to elastic contamination.

Figure 1 shows the TOF spectra of m/e 30, 31 and 32 at the center-of-mass angle. The m/e 30 and 31 spectra appear similar and peak at the same velocity, with the strong elastic contribution of m/e 32 appearing as a shoulder on the high velocity side of m/e 31 spectrum. By subtracting the m/e 32 contribution from the m/e 31 distribution we obtain a spectrum (solid line in Fig. 1b) which is identical to the m/e 30 spectrum (Fig. 1a). This strongly suggests that m/e 31 and m/e 30 have the same origin. Moreover, the intensity ratio of the m/e 30 and 31 TOF spectra is constant at different angles, giving further support that m/e 30 detected is a fragment of CH_3O (or CH_2OH), the primary reaction product, in the ionizer of the mass spectrometer. The narrow angular distribution of m/e 30 product also supports our contention that the primary reaction is not the highly exoergic ($\Delta H = -113 \text{ kcal/mole}$)¹¹ $\text{H}_2\text{CO} + \text{H}_2$ reaction. The H elimination channel can be accompanied by either CH_3O or CH_2OH radical formation, having slightly different exoergicities¹² (33 and 43 kcal/mole, respectively), but the two pathways cannot be distinguished in our experiment. The fact that we do not observe formaldehyde as a product suggests that the H_2 elimination channel from CH_3OH^+ plays a very minor role. The identification of the CH_3O (or CH_2OH) radical as one of the primary reaction products from the single bimolecular

reactive collision of $O(^1D_2)$ with CH_4 is unambiguous in our experiment. This certainty is not possible using mass spectrometric identification alone.

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*Brief version of LBL-9762, submitted to J. Chem. Phys.

FIGURE CAPTION

Fig. 1. a) Experimental TOF distribution of m/e 30 product in time space. The dark line is drawn through the data for clarity.

b) Experimental TOF distributions of m/e 31 (o) and m/e (Δ) in time space. The dark line represents m/e 31 TOF distribution corrected for m/e 32 contribution (see text). Other dotted or dashed lines are drawn through the data for clarity. Error bars ($\pm 2\sigma$) are of the size of the data points for m/e 32 TOF distribution. XBL-798-11136

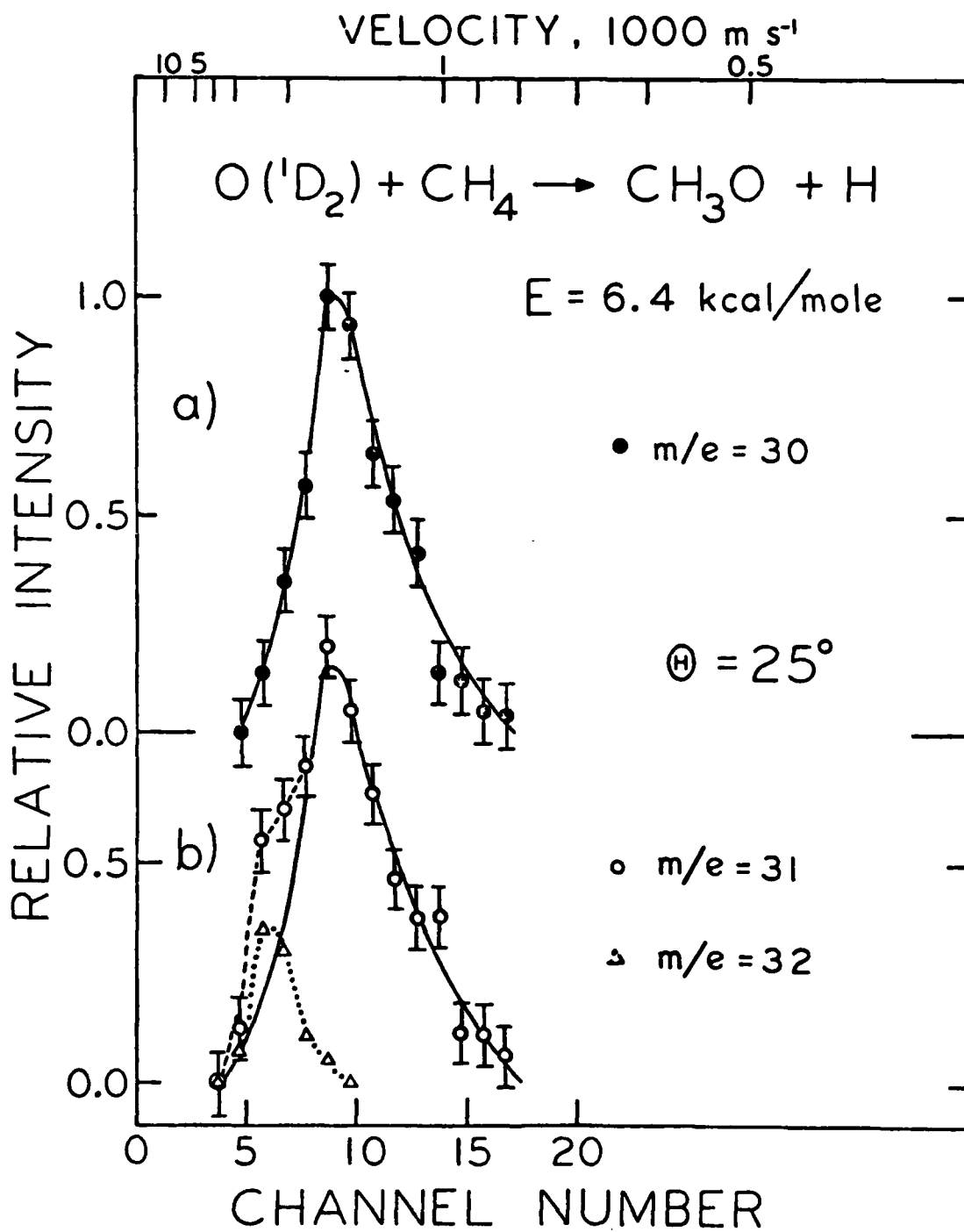


Fig. 1

XBL 798-11136

II. Publication of ONR Supported Research

A. Papers published or in press.

1. Development of a Supersonic Atomic Oxygen Nozzle Beam Source for Crossed Beam Scattering Experiments. Steven J. Sibener, Richard J. Buss and Yuan T. Lee "Rarefied Gas Dynamics", Eleventh International Symposium on Rarefied Gas Dynamics, Volume 2, page 981, Commissariat A L'Energie Atomique, Paris, 1979 (edited by R. Campargue).

ABSTRACT

A high pressure, supersonic, radio frequency discharge nozzle beam source has been developed for the production of intense beams of ground state oxygen atoms. An efficient impedance matching scheme has been devised for coupling the radio frequency power to the plasma as a function of both gas pressure and composition. Techniques for localizing the discharge directly behind the orifice of a water-cooled quartz nozzle have also been developed. The above combine to yield an atomic oxygen beam source which produces high molecular dissociation in oxygen seeded rare gas mixtures at total pressures up to 200 torr: 80-90% dissociation for oxygen/argon mixtures and 60-70% for oxygen/helium mixtures. Atomic oxygen intensities are found to be greater than 10^{17} atom sr^{-1} sec^{-1} . A brief discussion of the reaction dynamics of $\text{O} + \text{ICl} \rightarrow \text{IO} + \text{Cl}$ is also presented.

2. Molecular Beam Studies of Unimolecular Reactions: $\text{Cl}, \text{F} + \text{C}_2\text{H}_3\text{Br}$, Richard J. Buss, Michael J. Coggiola and Yuan T. Lee, Faraday Society Discussions of Chemical Society, April 1979.

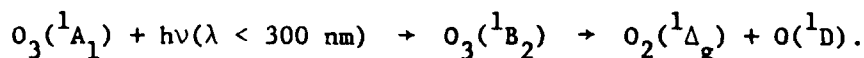
ABSTRACT

Several methods currently used to study unimolecular decomposition in molecular beams are discussed. We present experimental product angular and velocity distributions obtained for the reaction of F, Cl with $\text{C}_2\text{H}_3\text{Br}$. The mechanism by which conservation of angular momentum can cause coupling of the product angular and velocity distributions in dissociation of long-lived complexes is introduced.

3. 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 (1980) in press.

ABSTRACT

We have undertaken recently several studies on the photodissociation dynamics of small molecules. Since photodissociation mechanisms are poorly understood for systems other than diatomics, we have chosen ozone as a suitable molecule to study. Extensive theoretical and spectroscopic efforts have been made by other workers which renders a base of information complimentary 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



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

4. 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 (1980) in press.

ABSTRACT

A high pressure, radio frequency discharge nozzle beam source has been developed for the production of very intense ($> 10^{18}$ atoms sr^{-1} sec^{-1}) supersonic beams of oxygen atoms. An efficient impedance matching scheme has been devised for coupling the radio frequency power to oxygen-rare gas mixtures as a function of gas pressure, temperature, and composition. Techniques for localizing the discharge directly behind the orifice of a specially designed quartz nozzle have also been developed. The above combine to yield a beam source which reliably produces a high degree of molecular dissociation in oxygen-rare gas mixtures at pressures up to 350 torr. Atomic oxygen mean translational energies from 0.14 - 0.50 eV have been achieved using the seeded beams technique with Mach numbers up to 10 being realized. When helium is used as the carrier gas both $O(^3P_J)$ and $O(^1D_2)$ atoms are present in the

beam, while only ground state atoms appear to be present in argon seeded mixtures. This paper describes the design, construction, and operation of this beam source and provides a characterization of the atomic oxygen beams it has reproducibly generated in our laboratory.

5. A Crossed Molecular Beams Investigation of the Reactions $O(^3P) + C_6H_6, C_6D_6$. Steven J. Sibener, Richard J. Buss, Piergiorgio Casavecchia, Tomohiko Hirooka and Yuan T. Lee. J. Chem. Phys. 72 (1980) in press).

ABSTRACT

A crossed 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 products have been used to identify the major reaction pathways. The initially formed triplet biradical, C_6H_6O (C_6D_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. Invited Lectures presented during the contract period.

1. Y.T. Lee, Energetics and Dynamics of Molecule Ions by Molecular Beam Photoionization of van der Waals Molecules, Pauling Award Symposium on van der Waals Molecules, Seattle, Washington, January 20, 1979.
2. Y.T. Lee, Dynamics of Infrared Multiphoton Dissociation of Polyatomic Molecules, Department of Chemistry, Rice University, Houston, Texas, March 7, 1979.
3. Y.T. Lee, Investigation of Reaction Intermediates and Transient Species by the Molecular Beam Method, Department of Chemistry, Arizona State University, Tempe, Arizona, March 9, 1979.
4. Y.T. Lee, Dynamics of Multiphoton Dissociation in Molecular Beams, ACS/CSJ Chemical Congress: 1979, Laser Chemistry Symposium, Honolulu, Hawaii, April 2-6, 1979.
5. L.R. Carlson, Dynamics of the Photodissociation of Ozone, ACS/CSJ Chemical Congress: 1979, Laser Chemistry Symposium, Honolulu, Hawaii, April 2-6, 1979.
6. R.J. Buss, Molecular Beam Studies of Unimolecular Reactions, Cl , $\text{F} + \text{C}_2\text{H}_3\text{Br}$, Faraday General Discussion No. 67, "Kinetics of State-Selected Species, "University of Birmingham, England, April 9-11, 1979.
7. Y.T. Lee, Molecular Beam Studies of Infrared Multiphoton Dissociation of Polyatomic Molecules, Department of Chemistry, University of California, Los Angeles, California, April 24, 1979.
8. Y.T. Lee, Energetics and Dynamics of Radical Molecules, Department of Chemistry, University of California, Berkeley, May 1, 1979.
9. Y.T. Lee, Intramolecular Energy Transfer of Vibrationally Excited Molecules, Naval Weapons Laboratory, Washington, D.C., May 23, 1979.
10. Y.T. Lee, State to State Reactive Scattering, VI International Molecular Beam Symposium, Riva Del Garda, Italy, May 26-30, 1979.
11. R.K. Sparks, Dynamics of Photodissociation of O_3 , VI International Molecular Beam Symposium, Riva Del Garda, Italy, May 26-30, 1979.
12. Y.T. Lee, Infrared Multiphoton Dissociation of Polyatomic Molecules, CNEN, Centro di Frascati (Roma), Italy, June 7, 1979.
13. Y.T. Lee, Infrared Multiphoton Excitation and Dissociation of Molecules, Europhysics Study Conference on Multiphoton Processes, Benodet, France, June 18-22, 1979.

14. Y.T. Lee, Dynamics of IR Multiphoton Processes, Summer School on Chemical Photophysics, Les Houches, France, June 26, 1979.
15. Y.T. Lee, Molecular Beam Studies of Elementary Chemical Reactions, Summer School on Chemical Photophysics, Les Houches, France, June 27, 1979.
16. Y.T. Lee, Photoionization of Molecular Clusters, Summer School on Chemical Photophysics, Les Houches, France, June 28, 1979.
17. Y.T. Lee, Photoionization and Vibrational Predissociation of van der Waals Molecules, Herzberg International Conference on van der Waals Molecules, Quebec, Canada, August 1-3, 1979.
18. Y.T. Lee, Dynamics of Multiphoton Excitation Processes, Symposium on Atomic and Molecular Science, Taipei, China, August 23-25, 1979.
19. Tomohiko Hirooka, A Crossed Molecular Beam Study of the Reactions of $O(^3P) + C_6H_6$, C_6D_6 , XI International Conference on the Physics of Electronic and Atomic Collisions, Kyoto, Japan, August 29 - September 4, 1979.
20. K. Shobatake, Energy Disposal in the Photodissociation of CH_3I at 266 nm, XI International Conference on the Physics of Electronic and Atomic Collisions, Kyoto, Japan, August 29 - September 4, 1979.
21. R.J. Buss, Molecular Beam Studies of Substitution Reactions, American Chemical Society Meeting, Washington, D.C., September 9-14, 1979.
22. R.J. Buss, The Crossed Beam Studies on Reactions of $O(^3P)$ and $O(^1D)$, Combustion Symposium, Brookhaven National Laboratory, Upton, New York, October 9-11, 1979.
23. Y.T. Lee, Reaction Dynamics of $F + H_2$, D_2 , Third International Congress of Quantum Chemistry, Kyoto, Japan, October 29 - November 3, 1979.