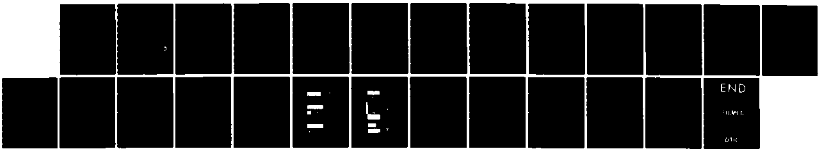
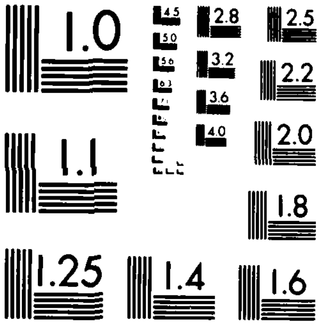
AD-A153 769 QUANTUM MODEL OF DEPHASING-ENHANCED LASER DESORPTION: 1/1
MASTER EQUATION APPROACH(U) ROCHESTER UNIV NY DEPT OF
CHEMISTRY J T LIN ET AL. APR 85 UROCHESTER/DC/85/TR-61
UNCLASSIFIED N00014-80-C-0472 F/G 20/5 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

②

OFFICE OF NAVAL RESEARCH

Contract N00014-80-C-0472

Task No. NR 056-749

TECHNICAL REPORT No. 61

Quantum Model of Dephasing-Enhanced Laser Desorption: Master Equation Approach

by

Jui-teng Lin, Xi-Yi Huang and Thomas F. George

Prepared for Publication

in

Journal of Vacuum Science and Technology B

Department of Chemistry
University of Rochester
Rochester, New York 14627

April 1985

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	**1b. RESTRICTIVE MARKINGS**
2a. SECURITY CLASSIFICATION AUTHORITY	**3. DISTRIBUTION/AVAILABILITY OF REPORT** Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) UROCHESTER/DC/85/TR-61	**5. MONITORING ORGANIZATION REPORT NUMBER(S)**
6a. NAME OF PERFORMING ORGANIZATION Department of Chemistry University of Rochester **6b. OFFICE SYMBOL** *(If applicable)*	**7a. NAME OF MONITORING ORGANIZATION** Office of Naval Research (Code 413)
6c. ADDRESS *(City, State and ZIP Code)* River Station Rochester, New York 14627	**7b. ADDRESS** *(City, State and ZIP Code)* Chemistry Program 800 N. Quincy Street Arlington, Virginia 22217
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Research **8b. OFFICE SYMBOL** *(If applicable)*	**9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER** Contract N00014-80-C-0472
8c. ADDRESS *(City, State and ZIP Code)* Chemistry Program 800 N. Quincy Street Arlington, Virginia 22217	**10. SOURCE OF FUNDING NOS.**

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
61153N	013-08	NR 056-749	

11. TITLE
Quantum Model of Dephasing-Enhanced Laser Desorption: Master Equation Approach

12. PERSONAL AUTHOR(S) Jui-teng Lin, Xi-Yi Huang and Thomas F. George

13a. TYPE OF REPORT	**13b. TIME COVERED**	**14. DATE OF REPORT** *(Yr., Mo., Day)*	**15. PAGE COUNT**
Interim Technical	FROM ______ TO ______	April 1985	18

16. SUPPLEMENTARY NOTATION
Prepared for publication in Journal of Vacuum Science and Technology B

17. COSATI CODES

FIELD	GROUP	SUB. GR.

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
LASER-INDUCED DESORPTION
LASER PULSE DURATION
MASTER EQUATION
ANHARMONICITY AND LASER DETUNING
BORN AND MARKOVIAN APPROXIMATIONS
DEPHASING

19. ABSTRACT *(Continue on reverse if necessary and identify by block number*

A new model for laser-induced desorption is proposed based on a master equation for the photon population in a closely-coupled subsystem involving the relevant degrees of freedom. The validity of approximations such as the Born and Markovian approximations is discussed in terms of the laser pulse duration and multiple time scales of the adspecies-surface system. The desorption rate is numerically calculated from the photon population and the threshold number of photons absorbed by the adspecies. The effects of anharmonicity, dephasing and laser detuning on the desorption rate are examined. The mechanism of dephasing and the possible direct and indirect desorption channels are discussed.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☒ DTIC USERS ☐	**21. ABSTRACT SECURITY CLASSIFICATION** Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. David L. Nelson	**22b. TELEPHONE NUMBER** *(Include Area Code)* (202) 696-4410 **22c. OFFICE SYMBOL**

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

Journal of Vacuum Science and Technology, in press

QUANTUM MODEL OF DEPHASING-ENHANCED LASER DESORPTION: MASTER EQUATION APPROACH

Jui-teng Lin
Laser Physics Branch
Optical Sciences Division
Naval Research Laboratory
Washington, D.C. 20375

Xi-Yi Huang and Thomas F. George
Department of Chemistry
University of Rochester
Rochester, New York 14627

Abstract

A new model for laser-induced desorption is proposed based on a master equation for the photon population in a closely-coupled subsystem involving the relevant degrees of freedom. The validity of approximations such as the Born and Markovian approximations is discussed in terms of the laser pulse duration and multiple time scales of the adspecies-surface system. The desorption rate is numerically calculated from the photon population and the threshold number of photons absorbed by the adspecies. The effects of anharmonicity, dephasing and laser detuning on the desorption rate are examined. The mechanism of dephasing and the possible direct and indirect desorption channels are discussed.

I. Introduction

Laser-stimulated surface processes (LSSP) have been investigated during the past several years, due both to their academic interest and industrial potential. Recent progress in experimental[1] and theoretical[2,3] studies and in applications[4] of LSSP has been reported. Laser excitation and/or desorption of adspecies have been investigated theoretically by a variety of techniques, including harmonic,[5] anharmonic[6] and Morse[7,8] potential models and master equation approaches,[7-16] where attention has been focused on the excitation of the active mode and the population of its vibrational states. The desorption rate is usually overestimated by the harmonic model,[5] whereas it is underestimated by the one-dimensional Morse potential model.[7,8]

In the present paper, we propose a new model in which all the degrees of freedom of a closely-coupled subsystem (including the active mode of the adspecies) are treated on an equal footing. The desorption rate is calculated from the photon population and the threshold number of photons absorbed by the adspecies as a whole, rather than from the average excitation of the active mode. In Section II, the generalized master equation is developed within the Born approximation, and a reduced master (rate) equation including the anharmonicity of the adspecies surface potential is investigated within the Markovian approximation. Numerical results are shown in Section III, where dephasing-enhanced desorption is suggested. In Section IV, the mechanism of dephasing and a variety of desorption channels are discussed.

II. Master Equation

Let us first define our model system, which is particularly appropriate for admolecules with very fast intramolecular relaxation. In the frequency domain, the total adspecies-surface system is divided into two subsystems,

S_1 and S_2, where S_1 consists of the active mode (A) and the strongly-coupled modes (B) within the adspecies, and S_2 consists of the remaining lower frequency modes serving as a heat bath (see Fig. 1). From the concept of the energy-gap law, we expect intramode relaxation within S_1 to be much faster than intersystem relaxation, i.e., $\gamma_{AB},\gamma_{BB} \gg \gamma_{BC},\gamma_{AC}$, where γ_{ij}^{-1} is the relaxation time between the i and j modes. When the system is irradiated by a laser field, S_1 will be excited through the active mode and its coupling to the B modes. The excitation rate of S_1, after a short time of γ_{AB}^{-1}, is proportional to the absorption cross section of the active mode. We can therefore express the interaction between the laser field and S_1 as

$$H_{SF}(t) = V(t)(a^{\dagger}+a), \tag{1}$$

where $V(t) \propto \gamma_{AB}\mu' E(t)\cos(\omega t)$ is proportional to the derivative of the active-mode dipole moment, μ', the coupling factor between A and B, γ_{AB}, and the laser field amplitude, E(t), with a frequency ω which is near-resonant to that of the active mode. $a^{\dagger}$ and a are the ladder operators for S_1 defined in photon space, i.e., $a^{\dagger}|n\rangle = \sqrt{n+1}\,|n+1\rangle$, where $|n\rangle$ is a basis function for S_1 as a whole, rather than for just the active mode which reaches steady state in the time γ_{AB}^{-1}.

The vibrational Hamiltonian of the system is

$$H = H_{S_1} + H_{S_2} + H_S + H_{SF}(t), \tag{2}$$

where H_S couples S_1 and S_2 (it is generally time-independent). The density matrix for the total system obeys the Liouville equation[16]

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H,\rho] \equiv -\frac{i}{\hbar}(L_{S_1}+L_{S_2}+L_S+L_{SF})\rho. \tag{3}$$

Within the Born approximation, $L_{S_1} + L_{S_2} + L_S \approx L_{S_1} + L_{S_2}$, and for Markovian processes where the characteristic time of the heat bath (S_2) is much shorter than other time scales of the system, the S_2 variables may be eliminated. We can then work with a reduced density matrix, $\bar{\rho} \equiv \mathrm{Tr}_B(\rho)$, which obeys the equation

$$\frac{d\bar{\rho}}{dt} = -\frac{i}{\hbar}(L_{S_1}+L_0-iL_1+L_{SF})\bar{\rho}, \qquad (4)$$

where the effects of the interaction between S_1 and S_2, L_S, are now reduced to a constant frequency shift, L_0, and a damping factor, L_1. We now introduce the Markovian approximation for the relaxation associated with L_S (assumed to be time independent), but retain memory effects due to the off-diagonal matrix elements associated with the laser excitation. For a Hamiltonian such as given by Eq.(1), we obtain a generalized master equation for the diagonal matrix element, $P_n \equiv [\mathrm{Tr}_B\rho]_{nn}$, as[9] (detailed discussions of the generalized master equation are available in the literature[16-18])

$$\frac{dP_n}{dt} = \gamma_1[(n+1)P_n - nP_n]$$

$$+ \int_0^t dt'\{W_{n,n-1}(t-t')[P_{n-1}(t')-P_n(t')] + W_{n,n+1}(t-t')[P_{n+1}(t')-P_n(t')]\}, \qquad (5)$$

with the time-dependent photon absorption/emission rates given by

$$W_{n,n+1}(\tau) = 2(n+1)\,\Omega(t)\,\Omega(t')e^{-i\Gamma\tau}\cos(\Delta_{n+1}\tau) \qquad (6)$$

$$W_{n,n-1}(\tau) = 2n\,\Omega(t)\,\Omega(t')\,e^{-i\Gamma\tau}\cos(\Delta_n\tau), \qquad (7)$$

Here, $\Omega(t) = V(t)/\cos(\omega t)$; $\tau = t-t'$; $\Delta_m = \omega_{mn} - \omega = \Delta - 2\epsilon m$, where ω_{mn} is the transition frequency between levels m and n, $\Delta = \omega_{10} - \omega$ is the laser detuning with respect to the fundamental frequency ω_{10}, and ϵ is the anharmonicity;

and $\Gamma = \gamma_1/2 + \gamma_2$ is the total damping associated with the off-diagonal matrix elements, where γ_1 and γ_2 denote the energy and (pure) dephasing factors, respectively. We have used the rotating-wave approximation and the dipole transition for the n dependence of $W_{m,n}$ (such that $m = n \pm 1$) for absorption ($m < n$) and emission ($m > n$). Note that P_n is the probability of the adspecies as a whole (S_1 subsystem) absorbing n photons, in which the active-mode state is given by its steady-state excitation, i.e., $n_A(\text{s.s.}) = \gamma_{AB}\sigma I/\hbar\omega$, where σ is the steady-state absorption cross section.

For a very short laser pulse with duration $t_p \lesssim \Gamma^{-1}$, the transient solution of Eq.(5) contains the memory effects of the population function, and the Markovian approximation may not be applied to this time-dependent excitation. We shall, instead, focus on the case of a long pulse excitation, e.g., a CO_2 laser pulse with $t_p \simeq 10$ ns which is much longer than the dephasing time Γ^{-1}, such that the population function $P_n(t)$ and $\Omega(t)$ are slowly varying and may be factored out of the integrals in Eq.(5). Employing this adiabatic, Markovian approximation, the transition rates $W_{m,n}$ have no memory effects, although they are still time dependent due to the laser temporal profile E(t), and a simpler master equation is then obtained:[9,16]

$$\frac{dP_n}{dt} = \gamma_1[(n+1)P_{n+1}-nP_n] + 2\Gamma\Omega^2(t)\left\{\frac{n(P_{n-1}-P_n)}{[\Delta-2\varepsilon(n-1)]^2+\Gamma^2} + \frac{(n+1)(P_{n+1}-P_n)}{(\Delta-2\varepsilon n)^2+\Gamma^2}\right\}. \quad (8)$$

Several features of this equation are: (i) the absorption cross section for the adspecies (S_1 subsystem) is saturated at a higher photon population due to the anharmonicity; (ii) the first two terms describe the actual energy flow from S_1 to the surface (S_2); (iii) the pure dephasing factor (γ_2) changes only the intramolecular phase without changing the energy populations; (iv) the multiphonon relaxation factor (γ_1) is generally strongly temperature dependent and is a strongly decreasing function of the energy gap between S_1 and S_2; (v) the remaining terms containing the factor Γ indicate that the effect of the applied field is always intimately related to the phase dissipation or broadening mechanisms.

Equation (8) may be referred to as the usual rate equation in which no memory effects are preserved either in the relaxation or the excitation process. For weaker dephasing systems subject to a short pulse excitation, the "most general" form of the generalized master equation is given by Eq.(5) in which the relaxation terms are replaced by[18]

$$\frac{2}{\hbar^2} \mathrm{Re} \sum_m \int_0^t dt' < H_S'(t) H_S'(t') > [P_m(t') - P_n(t')] e^{-(i\omega_{mn}+\Gamma_{mn})(t-t')} , \qquad (9)$$

where $\Gamma_{mn} = (\gamma_m+\gamma_n)/2 + \gamma_2$ is the total surface-induced damping. Furthermore, for a short-pulsed laser with high intensity, the Born approximation may not be valid. Improvements can be made by performing a trace over the photon(laser)-dressed states of the heat bath (S_2). For the case of strong coupling between S_1 and S_2, H_S' may not be used as a perturbation, and again the Born approximation is questionable. To go beyond this, we may carry out a unitary transformation on S_1 with subsequent laser interaction with the phonon(surface)-dressed states.[2] These improvements allow for both multiphonon (relaxation) and multiphoton (excitation) processes. The absorption cross section for the S_1 subsystem, for example, will be related to the laser intensity by a power law $\sigma \propto I^n$ for n-photon processes. We also note that a nonlinear power law, $\sigma \propto I^m$ with $m < 1$, is also possible by anharmonic saturation.[3]

III. Desorption Rate

For a first-order desorption process, the rate constant is related to the inverse of the mean first-passage time, $\bar{t}$, and is given by[19]

$$K_D = \frac{1}{\bar{t}} = \left(\sum_{n=0}^{n^*} \int_0^\infty dt \; P_n(t) \right)^{-1}, \tag{10}$$

where n* is the desorption threshold number of photons absorbed by the adspecies. Numerical results are shown in Figs. 2 and 3. From Fig. 2 we see that the desorption rate is a strongly-decreasing function of the anharmonicity. Dephasing-enhanced desorption is seen in Fig. 3, where an optimal value at $\gamma_2 \simeq 1.8$ is found for a maximal desorption rate. This is realized by the fact that the dephasing tends to compensate for anharmonicity "bottleneck" effects. An enhancement factor of about 3 is possible if we tune the dephasing to the optimal value of $\gamma_2 \simeq 1.8$, in comparison with $\gamma_2 = 4$. We note that the dephasing-enhanced effects caused by the nonlinear behavior are absent in a harmonic model, where K_D is always a decreasing function of γ_2.

In Fig. 4 we show the time evolution of the desorption probability, defined by

$$P_D(t) = \sum_{n=n^*}^{\infty} P_n(t). \tag{11}$$

Again, we see the nonlinear behavior of the dephasing effects. For a fixed time, say t = 100 units, P_D increases when γ_2 increases from 1 to 5, but it decreases at higher values of γ_2.

IV. Discussion

A. Mechanism of Dephasing

As indicated in the previous section, the dephasing factor changes only the phase of the excited subsystem S_1 without changing its energy populations. In the language of gas-phase scattering theory, this can be referred to as an "elastic" scattering process. In the presence of a laser field, dephasing can be viewed as energy transfer from the excited subsystem to a "virtual" state of the field and back to the original excited state. Within the adspecies/surface system itself, the dephasing is due to one or more of the following:[6,20,21] (i) dephasing of the active dipole of the adspecies (or dephasing of the laser field itself); (ii) fluctuation of the conformation of the adspecies due to the thermal energy provided by either the initial surface temperature or laser-heating effects; (iii) librational and rotational relaxation within the vibrational manifold of the excited S_1 subsystem; (iv) intramolecular mode-mode coupling within S_1 and intermolecular coupling between S_1 and S_2; (v) lateral motion or migration-induced elastic collisions between adspecies and with the substrate surface; (vi) surface phonon-dispersion-induced level broadening of the vibrational manifold.

We note that the dephasing factor γ_2, introduced in Section II, is formally derived from the Liouville equation within the Markovian approximation, where the laser field amplitude is assumed to be generated by a coherent source. However, the field itself may often be only partially coherent and hence will cause additional dephasing of the excited subsystem. To demonstrate this mathematically, we start with the reduced density matrix equation of motion for $P_{mn} \equiv [\mathrm{Tr}_B \rho]_{mn}$, $m \neq n$,

$$\frac{dP_{mn}}{dt} = -i[\omega_{mn} + \bar{\omega}(t)]P_{mn}, \tag{12}$$

where we have introduced a stochastic frequency shift of the system, $\bar{\omega}(t)$, caused by the partially coherent behavior of the laser field. By assuming a "white noise," $\langle\omega(t)\rangle = 0$, and a Markovian correlation, $\langle\bar{\omega}(t)\bar{\omega}(t')\rangle = \bar{\gamma}_2\,\delta(t-t')$, we obtain an ensemble-averaged (over the stochastic variable) equation

$$\left\langle\frac{dP_{mn}}{dt}\right\rangle = -\,[i\omega_{mn} + (\Gamma_{mn} + \bar{\gamma}_2)]\langle P_{mn}\rangle, \tag{13}$$

where $\bar{\gamma}_2$ is the laser-induced dephasing.[21]

B. Mechanism of Desorption

The desorption mechanism, which may involve several channels, depending on the nature of the adspecies (e.g., physisorbed or chemisorbed, adatom or admolecule, and the potential of the adbond), and the associated energy levels of the system are shown in Fig. 5. The desorption may result from direct laser excitation or indirect energy transfer processes. The details of the desorption channels from Type I to Type VI have been discussed previously[3,4]. As a concluding remark, we note that a complete description of laser-induced desorption should at least include the competing processes, e.g., migration-induced desorption and re-adsorption after the mean first-passage time. Furthermore, for systems with more than one active mode, desorption may occur via a two-stage process: the initial stage of absorbing n* photons followed by thermal phonon-assisted and/or V-V energy transfer among the excited active modes. This type of process is under investigation in our laboratories.

Acknowledgment

This research was supported in part by the Office of Naval Research and the Air Force Office of Scientific Research (AFSC), United States Air Force, under Grant AFOSR-82-0046. The United States Government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright notation hereon. TFG acknowledges the Camille and Henry Dreyfus Foundation for a Teacher-Scholar Award (1975-86).

References

1. T. J. Chuang, Surf. Sci. Rep. 3, 1 (1983).

2. T. F. George, J. Lin, A. C. Beri and W. C. Murphy, Prog. Surf. Sci. 16, 139 (1984).

3. J. Lin, M. Hutchinson and T. F. George, in Advances in Multi-Photon Processes and Spectroscopy, Vol. 1, ed. by S. H. Lin (World Scientific, Singapore, 1984), pp. 105-237.

4. J. Lin, W. C. Murphy and T. F. George, Ind. Eng. Chem. Prod. Res. Dev. 23, 334 (1984).

5. M. S. Slutsky and T. F. George, Chem. Phys. Lett. 57, 474 (1978); J. Chem. Phys. 70, 1231 (1979).

6. J. Lin and T. F. George, J. Chem. Phys. 72, 2554 (1980); 78, 5197 (1983).

7. C. Jedrzejek, K. F. Freed, S. Efrima and H. Metiu, Surf. Sci. 109, 191 (1981).

8. Z. W. Gortel, H. J. Kreuzer, P. Piercy and R. Teshima, Phys. Rev. B 27, 5066 (1983); H. J. Kreuzer and Z. W. Gortel, Phys. Rev. B 29, 6926 (1984).

9. J. Lin and T. F. George, Surf. Sci. 115, 569 (1982).

10. J. Lin and T. F. George, Chem. Phys. Lett. 66, 5 (1979).

A. C. Beri and T. F. George, J. Chem. Phys. 78, 4288 (1983).

12. A. C. Beri and T. F. George, J. Chem. Phys., submitted.

13. A. C. Beri and T. F. George, J. Vac. Sci. Technol., submitted.

14. B. Fain and S. H. Lin, Surf. Sci. 147, 497 (1984).

15. G. S. Wu, B. Fain, A. R. Ziv and S. H. Lin, Surf. Sci. 147, 537 (1984).

16. X. Y. Huang, T. F. George, J. M. Yuan and L. M. Narducci, J. Phys. Chem. 88, 5772 (1984); X. Y. Huang, T. F. George and J. M. Yuan, J. Opt. Soc. Am. B, in press.

17. W. H. Louisell, Quantum Statistical Properties of Radiation (Wiley, New York, 1973), Chapt. 6.

18. S. H. Lin and H. Eyring, Proc. Natl. Acad. Sci. U.S.A. 78, 2013 (1978).

19. E. W. Montroll and K. E. Shuler, Adv. Chem. Phys. 1, 361 (1958).

20. X. Y. Huang, J. Lin and T. F. George, J. Chem. Phys. 80, 893 (1984); X. Y. Huang and T. F. George, J. Chem. Phys. 88, 4801 (1984).

21. X. Y. Huang, J. D. Cresser and J. H. Eberly, J. Opt. Soc. Am. B, in press.

Figure Captions

1. Schematic diagram for the frequency spectrum of the total system $S_1 + S_2$, where $S_1 = A + B$, with the corresponding relaxation factors indicated.

2. Anharmonicity (ϵ) dependence of the desorption rate K_D in arbitrary units. The parameters used are $(\gamma_1, \gamma_2, \Omega_0, \Delta) = (0.1, 2.0, 0.1, 0.0)$, with a laser pulse duration of $t_p = 10$ ns, where $\Omega(t) = \Omega_0 \sin^2(\pi t/t_p)$. γ_1, γ_2, Ω_0 and Δ are in the unit of $10^{11}\ s^{-1}$, and $n^* = 3$ has been used in Eq.(10).

3. Phase-relaxation (γ_2) dependence of K_D. The parameters used are $(\gamma_1, \Omega_0, \epsilon, \Delta, t_p) = (0.5, 0.1, 1, 3, 10)$. The envelope function of the laser pulse is the same as in Fig. 2.

4. Time dependence of the desorption probability $P_D(t)$, where $n^* = 3$ has been used in this calculation. A cw laser field has been assumed, and the other parameters are $(\gamma_1, \Omega_0, \epsilon, \Delta) = (0.01, 0.1, 1.5, 3.0)$.

5. Schematic diagrams of adspecies-surface systems and the associated energy levels, where A, B and M represent the adspecies (adatom or admolecule), C represents the substrate (or bath modes), and the laser radiation is indicated by the wiggly lines. Several types of desorption channels are illustrated: (I) direct desorption via active-mode excitation, (II) direct desorption via the quasi-continuum, (III) indirect desorption via tunneling, (IV) indirect desorption via substrate heating, (V) phonon-assisted desorption and (VI) indirect desorption via dynamics.

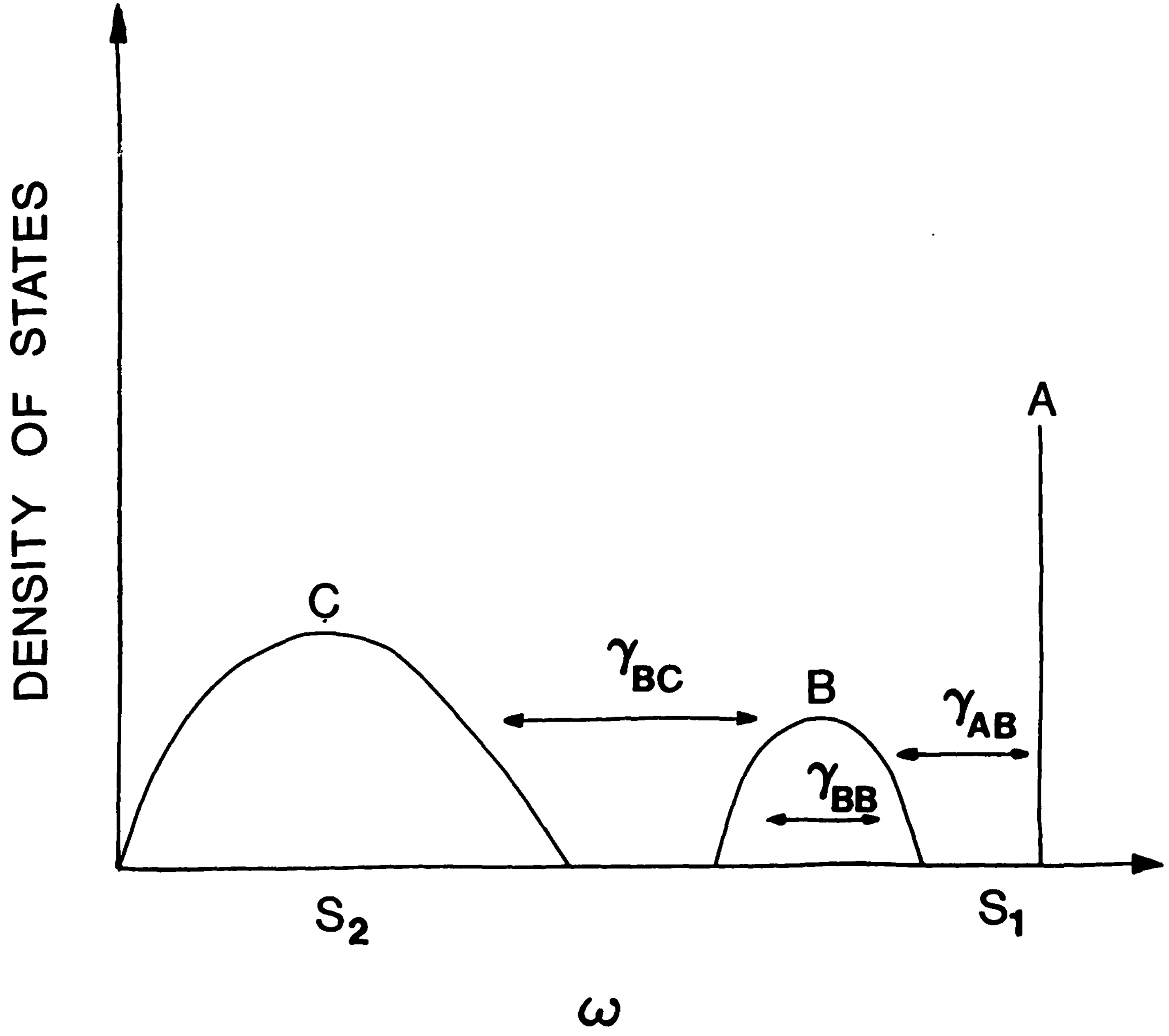
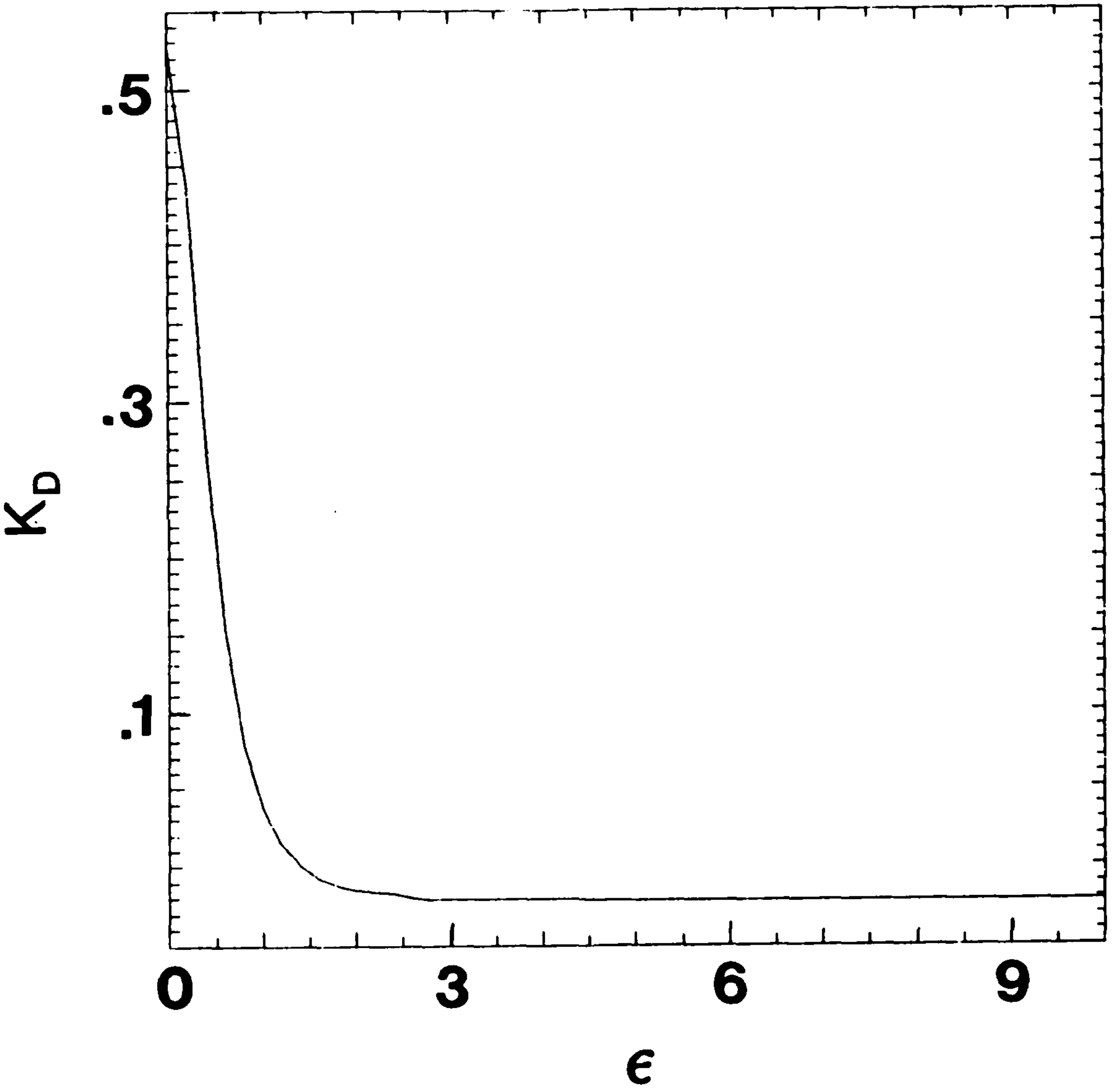


Fig. 1



Fig

L 1

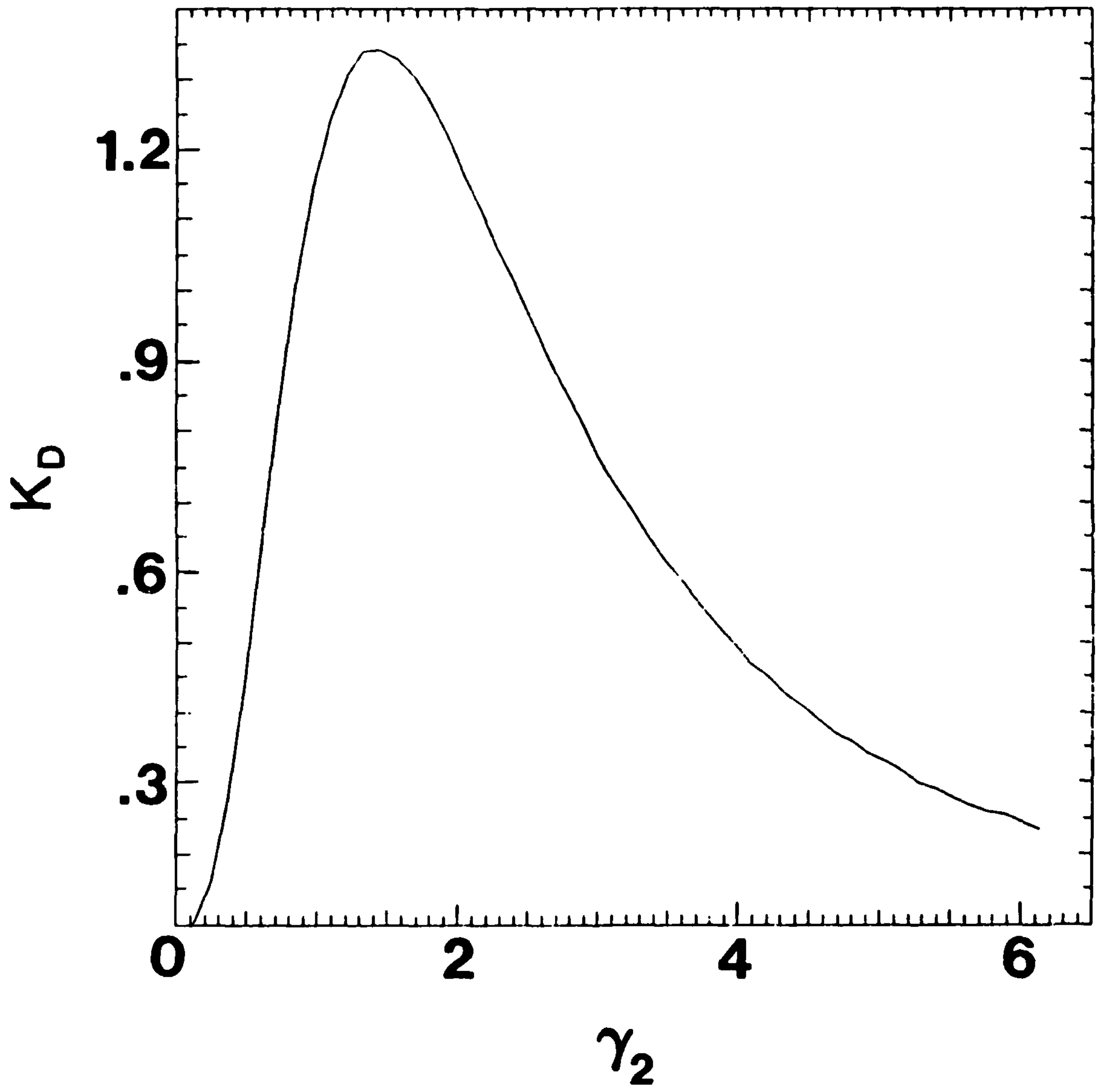
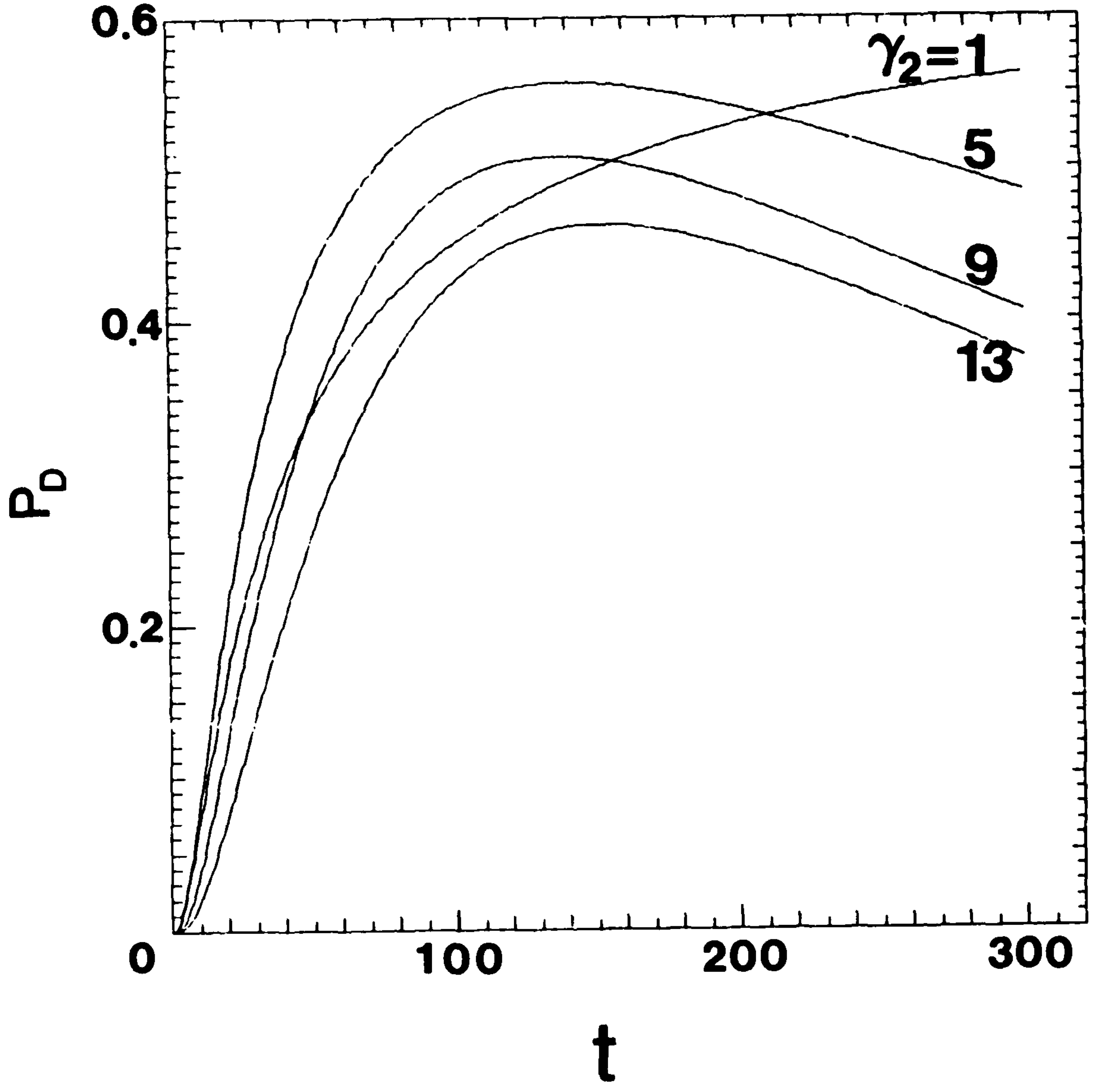


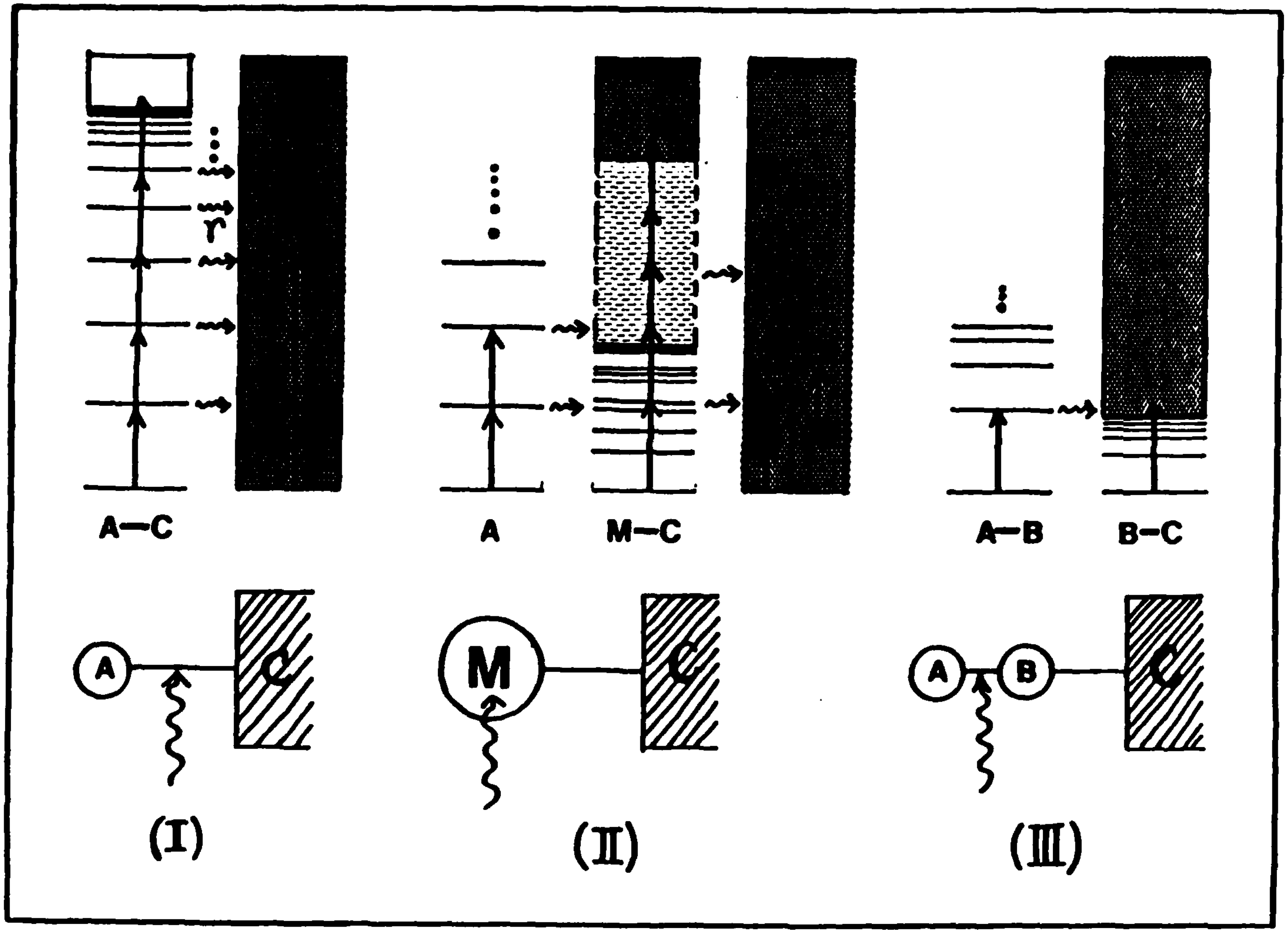
Fig.

Lin et al

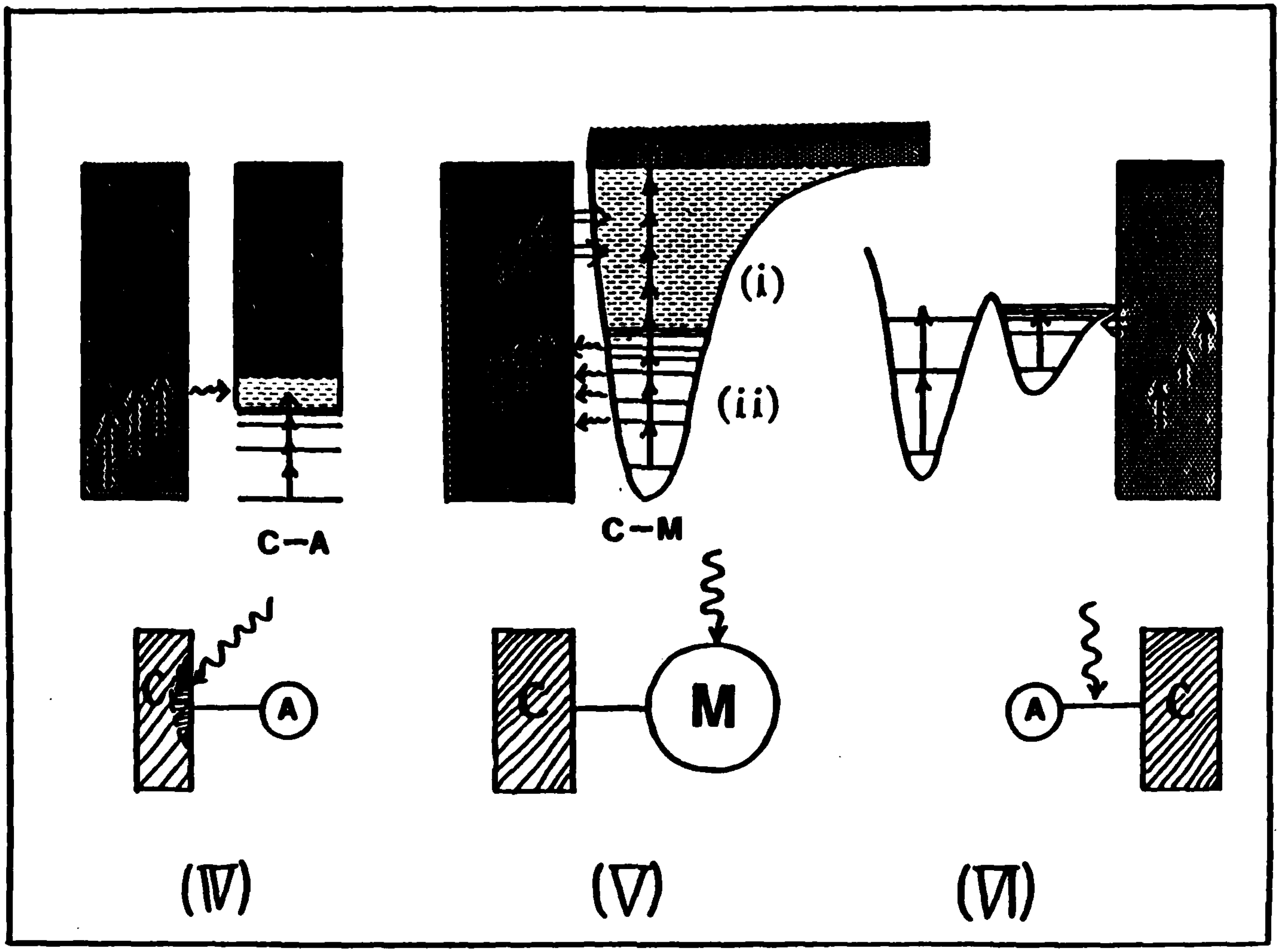


F[illegible]

Lin [illegible]



Lin et al
Fig. 5 (I)-(III)



Lin et al
Fig. 5 (IV)-(VI)

DL/413/83/01
GEN/413-2

TECHNICAL REPORT DISTRIBUTION LIST, GEN

	No. Copies
Office of Naval Research Attn: Code 413 800 N. Quincy Street Arlington, Virginia 22217	2
Dr. Bernard Douda Naval Weapons Support Center Code 5042 Crane, Indiana 47522	1
Commander, Naval Air Systems Command Attn: Code 310C (H. Rosenwasser) Washington, D.C. 20360	1
Naval Civil Engineering Laboratory Attn: Dr. R. W. Drisko Port Hueneme, California 93401	1
Defense Technical Information Center Building 5, Cameron Station Alexandria, Virginia 22314	12
DTNSRDC Attn: Dr. G. Bosmajian Applied Chemistry Division Annapolis, Maryland 21401	1
Dr. William Tolles Superintendent Chemistry Division, Code 6100 Naval Research Laboratory Washington, D.C. 20375	1
Dr. David Young Code 334 NORDA NSTL, Mississippi 39529	1
Naval Weapons Center Attn: Dr. A. B. Amster Chemistry Division China Lake, California 93555	1
Scientific Advisor Commandant of the Marine Corps Code RD-1 Washington, D.C. 20380	1
U.S. Army Research Office Attn: CRD-AA-IP P.O. Box 12211 Research Triangle Park, NC 27709	1
Mr. John Boyle Materials Branch Naval Ship Engineering Center Philadelphia, Pennsylvania 19112	1
Naval Ocean Systems Center Attn: Dr. S. Yamamoto Marine Sciences Division San Diego, California 91232	1
Dr. David L. Nelson Chemistry Division Office of Naval Research 800 North Quincy Street Arlington, Virginia 22217	1

DL/413/83/01
056/413-2

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. G. A. Somorjai
Department of Chemistry
University of California
Berkeley, California 94720

Dr. J. Murday
Naval Research Laboratory
Surface Chemistry Division (6170)
455 Overlook Avenue, S.W.
Washington, D.C. 20375

Dr. J. B. Hudson
Materials Division
Rensselaer Polytechnic Institute
Troy, New York 12181

Dr. Theodore E. Madey
Surface Chemistry Section
Department of Commerce
National Bureau of Standards
Washington, D.C. 20234

Dr. J. E. Demuth
IBM Corporation
Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, New York 10598

Dr. M. G. Lagally
Department of Metallurgical
and Mining Engineering
University of Wisconsin
Madison, Wisconsin 53706

Dr. R. P. Van Duyne
Chemistry Department
Northwestern University
Evanston, Illinois 60637

Dr. J. M. White
Department of Chemistry
University of Texas
Austin, Texas 78712

Dr. D. E. Harrison
Department of Physics
Naval Postgraduate School
Monterey, California 93940

Dr. W. Kohn
Department of Physics
University of California, San Diego
La Jolla, California 92037

Dr. R. L. Park
Director, Center of Materials
Research
University of Maryland
College Park, Maryland 20742

Dr. W. T. Peria
Electrical Engineering Department
University of Minnesota
Minneapolis, Minnesota 55455

Dr. Keith H. Johnson
Department of Metallurgy and
Materials Science
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dr. S. Sibener
Department of Chemistry
James Franck Institute
5640 Ellis Avenue
Chicago, Illinois 60637

Dr. Arold Green
Quantum Surface Dynamics Branch
Code 3817
Naval Weapons Center
China Lake, California 93555

Dr. A. Wold
Department of Chemistry
Brown University
Providence, Rhode Island 02912

Dr. S. L. Bernasek
Department of Chemistry
Princeton University
Princeton, New Jersey 08544

Dr. P. Lund
Department of Chemistry
Howard University
Washington, D.C. 20059

DL/413/83/01
056/413-2

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. F. Carter
Code 6132
Naval Research Laboratory
Washington, D.C. 20375

Dr. Richard Colton
Code 6'12
Naval Research Laboratory
Washington, D.C. 20375

Dr. Dan Pierce
National Bureau of Standards
Optical Physics Division
Washington, D.C. 20234

Dr. R. Stanley Williams
Department of Chemistry
University of California
Los Angeles, California 90024

Dr. R. P. Messmer
Materials Characterization Lab.
General Electric Company
Schenectady, New York 22217

Dr. Robert Gomer
Department of Chemistry
James Franck Institute
5640 Ellis Avenue
Chicago, Illinois 60637

Dr. Ronald Lee
R301
Naval Surface Weapons Center
White Oak
Silver Spring, Maryland 20910

Dr. Paul Schoen
Code 5570
Naval Research Laboratory
Washington, D.C. 20375

Dr. John T. Yates
Department of Chemistry
University of Pittsburgh
Pittsburgh, Pennsylvania 15260

Dr. Richard Greene
Code 5230
Naval Research Laboratory
Washington, D.C. 20375

Dr. L. Kesmodel
Department of Physics
Indiana University
Bloomington, Indiana 47403

Dr. K. C. Janda
California Institute of Technology
Division of Chemistry and Chemical
Engineering
Pasadena, California 91125

Dr. E. A. Irene
Department of Chemistry
University of North Carolina
Chapel Hill, Northc Carolina 27514

Dr. Adam Heller
Bell Laboratories
Murray Hill, New Jersey 07974

Dr. Martin Fleischmann
Department of Chemistry
Southampton University
Southampton 509 5NH
Hampshire, England

Dr. John W. Wilkins
Cornell University
Laboratory of Atomic and
Solid State Physics
Ithaca, New York 14853

Dr. Richard Smardzewski
Code 6130
Naval Research Laboratory
Washington, D.C. 20375

Dr. H. Tachikawa
Chemistry Department
Jackson State University
Jackson, Mississippi 39217

DL/413/83/01
056/413-2

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. R. G. Wallis
Department of Physics
University of California
Irvine, California 92664

Dr. D. Ramaker
Chemistry Department
George Washington University
Washington, D.C. 20052

Dr. J. C. Hemminger
Chemistry Department
University of California
Irvine, California 92717

~~Dr. T. F. George~~
~~Chemistry Department~~
~~University of Rochester~~
~~Rochester, New York 14627~~

Dr. G. Rubloff
IBM
Thomas J. Watson Research Center
P.O. Box 218
Yorktown Heights, New York 10598

Dr. Horia Metiu
Chemistry Department
University of California
Santa Barbara, California 93106

Captain Lee Myers
AFOSR/NC
Bollig AFB
Washington, D.C. 20332

Dr. J. T. Keiser
Department of Chemistry
University of Richmond
Richmond, Virginia 23173

Dr. Roald Hoffmann
Department of Chemistry
Cornell University
Ithaca, New York 14853

Dr. R. W. Plummer
Department of Physics
University of Pennsylvania
Philadelphia, Pennsylvania 19104

Dr. E. Yeager
Department of Chemistry
Case Western Reserve University
Cleveland, Ohio 41106

Dr. N. Winograd
Department of Chemistry
Pennsylvania State University
University Park, Pennsylvania 16802

Dr. G. D. Stein
Mechanical Engineering Department
Northwestern University
Evanston, Illinois 60201

Dr. A. Steckl
Department of Electrical and
Systems Engineering
Rensselaer Polytechnic Institute
Troy, NewYork 12181

Dr. G. H. Morrison
Department of Chemistry
Cornell University
Ithaca, New York 14853

Dr. P. Hansma
Physics Department
University of California
Santa Barbara, California 93106

Dr. J. Baldeschwieler
California Institute of Technology
Division of Chemistry
Pasadena, California 91125

Dr. W. Goddard
California Institute of Technology
Division of Chemistry
Pasadena, California 91125

DL/413/83/01
056/413-2

ABSTRACTS DISTRIBUTION LIST, 056/625/629

r. J. E. Jensen
ughes Research Laboratory
011 Malibu Canyon Road
alibu, California 90265

r. J. H. Weaver
epartment of Chemical Engineering
  and Materials Science
niversity of Minnesota
inneapolis, Minnesota 55455

Dr. W. Knauer
Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, California 90265

Dr. C. B. Harris
Department of Chemistry
University of California
Berkeley, California 94720