4

OFFICE OF NAVAL RESEARCH

Grant N00014-90-J-1193

TECHNICAL REPORT No. 7

Decay Rate and Resonance Fluorescence Spectrum of a Molecule Near a Composite Material Surface

by

X.-S. Li, D. L. Lin, Thomas F. George, Y. Liu and Q.-Q. Gou

Prepared for Publication

in

Physics Letters A

Departments of Chemistry and Physics
State University of New York at Buffalo
Buffalo, New York 14260

March 1990

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE:

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S): UBUFFALO/DC/90/TR-7

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION:
Depts. Chemistry & Physics
State University of New York

6b. OFFICE SYMBOL *(If applicable)*:

7a. NAME OF MONITORING ORGANIZATION:

6c. ADDRESS *(City, State, and ZIP Code)*:
Fronczak Hall, Amherst Campus
Buffalo, New York 14260

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: Grant N00014-90-J-1193

8c. ADDRESS *(City, State, and ZIP Code)*:
Chemistry Program
800 N. Quincy Street
Arlington, Virginia 22217

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.

11. TITLE *(Include Security Classification)*: Decay Rate and Resonance Fluorescence Spectrum of a Molecule Near a Composite Material Surfac

12. PERSONAL AUTHOR(S): X.S. Li, D.L. Lin, Thomas F. George, Y. Liu, and Q.Q. Gou

13a. TYPE OF REPORT:

13b. TIME COVERED: FROM ________ TO ______

14. DATE OF REPORT *(Year, Month, Day)*: March 1990

15. PAGE COUNT: 14

16. SUPPLEMENTARY NOTATION: Prepared for publication in Physics Letters A

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*:
DECAY RATE; COMPOSITE SUBSTRATES;
RESONANCE FLUORESCENCE; SEMICONDUCTOR/DIELECTRIC PARTICLES;
MOLECULE NEAR SURFACE; DIELECTRIC/METALLIC PARTICLES.

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

The spontaneous decay rate and resonance fluorescence spectrum of a molecule near the surface of composite materials are calculated in the effective medium approximation. Two substrates are considered: One is a semiconductor containing randomly distributed small dielectric particles and the other a dielectric with metallic particles. Results are analyzed in terms of energy transfer from the molecule to the substrate as functions of the volume fraction of impurity particles.

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 *(Include Area Code)*: (202) 696-4410

22c. OFFICE SYMBOL:

Previous editions are obsolete.

Physics Letters A, in press

DECAY RATE AND RESONANCE FLUORESCENCE SPECTRUM OF A MOLECULE NEAR A COMPOSITE MATERIAL SURFACE

Xiao-shen Li, D. L. Lin, Thomas F. George and Yue Liu*
Department of Physics and Astronomy
State University of New York at Buffalo
Buffalo, New York 14260

Qing-Quan Gou
Chengdu University of Science and Technology
Institute of High Temperature and High Pressure Physics
Chengdu, Shichuang 610065
People's Republic of China

Abstract

The spontaneous decay rate and resonance fluorescence spectrum of a molecule adapted near the surface of composite materials are calculated in the effective medium approximation. Two substrates are considered: One is a semiconductor containing randomly distributed small dielectric particles and the other a dielectric with metallic particles. Results are analyzed in terms of energy transfer from the molecule to the substrate as functions of the volume fraction of impurity particles.

* On leave from Chengdu University of Science and Technology, Chengdu, China.

I. Introduction

Optical properties, both linear and nonlinear, of composite materials with small solid particles distributed randomly in an otherwise homogeneous medium have been a subject of extensive research in recent years.[1-5] We consider in this Letter the situation in which a molecule is located near the surface of a composite material. The material can be a semiconductor with small dielectric particles randomly distributed throughout its volume, or a dielectric containing small metallic particles. Our primary aim is to study how the volume fraction of the small particles affect the frequency dependence of optical properties of the adsorbed molecule, in particular, its spontaneous decay rate and light scattering spectrum. As a matter of fact, problems of this sort of adapted molecule have attracted much attention after the fatty-acid monolayer assembly technique[6] was developed to measure the luminescent lifetime of excited molecules near bulk solid surfaces. As has been shown in previous works on various materials,[7-10] optical properties of adapted molecules are greatly affected by the structure of the substrate. Therefore, the adapted molecule serves as a probe to explore the structure of the substrate near its surface.

II. Model

Consider a molecule with two levels $|+\rangle$ and $|-\rangle$ separated by a distance $\hbar\omega$ and adsorbed near the surface of a composite material. The molecule is driven by a monochromatic laser field with

$$E(t) = \frac{1}{2}\left(Ee^{i\omega_L t} + E^* e^{-i\omega_L t}\right) \quad (1)$$

We can apply the surface-dressed optical Bloch equations (SBE)[8,9] to describe the interaction process, which are given by[9]

$$\frac{d}{dt}\begin{bmatrix}<S^+>\\ <S^z>\\ <S^->\end{bmatrix} = \begin{bmatrix} i(\Delta+\Omega^s) - \gamma & i\Omega & 0 \\ i\Omega^*/2 & -2\gamma & -i\Omega/2 \\ 0 & -i\Omega^* & -i(\Delta+\Omega^s) - \gamma \end{bmatrix}\begin{bmatrix}<S^+>\\ <S^z>\\ <S^->\end{bmatrix} - \begin{bmatrix}0\\ \gamma\\ 0\end{bmatrix} . \quad (2)$$

The notation is as follows. The admolecule with a transition frequency ω is located at a distance d away from the surface of a composite solid. The matrix element of the electric dipole moment opertaor is denoted by $|p|$, and E and ω_L are the amplitude and frequency of the external laser field, respectively. The detuning is $\Delta = \omega - \omega_L$, and the Rabi frequency is $\Omega = |p|E$. The transition probability is proportional to the projection operators defined by

$$S^+ = |+\rangle\langle-| \quad .$$

$$S^z = \frac{1}{2}\,(|+\rangle\langle+| \; - \; |-\rangle\langle-|) \quad (3)$$

$$S^- = |-\rangle\langle+| \quad .$$

The total decay rate of the admolecule can be written as

$$\gamma = \gamma^o + \gamma^s \quad , \quad (4)$$

where γ^o is the decay rate in the absence of the substrate,

$$\gamma^o = \frac{2}{3} \sqrt{\epsilon_1} |p|^2 \omega^3 / c^3 \qquad (4a)$$

with ϵ_1 denoting the dielectric constant of the medium containing the molecule, and

$$\gamma^s = |p|^2 \ \mathrm{Im}\ f(d) \qquad (4b)$$

is the decay rate induced by the surface. The frequency shift of the spontaneous radiation due to the surface is

$$\Omega^s = |p|^2 \ \mathrm{Re}\ f(d) \quad , \qquad (5)$$

and the function f(d) is determined by[9]

$$E_R = |p| f(d) S^{-} = pf(d) \quad , \qquad (6)$$

where E_R is the component of the reflected field $\vec{E}_R$ in the direction of $\vec{p}$.

It is evident that the reflected electric field E_R depends on the structure and other information of the substrate. However complicated the dependence may be, it is contained in the function f(d) which can be determined by usual procedures as described in Refs. 7 and 9. For definiteness, we limit ourselves to the case in which the dipole moment of the admolecule is perpendicular to the substrate surface. The decay rate and frequency shift of the molecule at a distance d from the surface expressed in the unit γ^o are given by[7]

$$\gamma^{s} = -\frac{3}{2}\,\mathrm{Re}\int_0^\infty \frac{\kappa^3 d\kappa}{\mu_1}\,\frac{\epsilon_1\mu_2 - \epsilon_2\mu_1}{\epsilon_1\mu_2 + \epsilon_2\mu_1}\,e^{2i\mu_1\hat{d}} \qquad (7)$$

$$\Omega^{s} = \frac{3}{2}\,\mathrm{Im}\int_0^\infty \frac{\kappa^3 d\kappa}{\mu_1}\,\frac{\epsilon_1\mu_2 - \epsilon_2\mu_1}{\epsilon_1\mu_2 + \epsilon_2\mu_1}\,e^{2i\mu_1\hat{d}} \quad , \qquad (8)$$

where ϵ_2 is the effective dielectric constant of the composite substrate, $\mu_1 = \sqrt{1 - \kappa^2}$, $\mu_2 = \sqrt{\epsilon_2/\epsilon_1 - \kappa^2}$ and $\hat{d} = \sqrt{\epsilon_1}\,\omega d/c$.

In the composite substrate, we assume that small particles of spherical shape are randomly distributed throughout its volume. Thus, we can employ the effective-medium approximation[3,5,11] as used in the study of linear dielectric properties of composites. In this approximation the effective dielectric constant ϵ_2 is determined by the equation

$$(1-P)\,\frac{\epsilon_a - \epsilon_2}{\epsilon_a + 2\epsilon_2} + P\,\frac{\epsilon_b - \epsilon_2}{\epsilon_b + 2\epsilon_2} = 0 \quad , \qquad (9)$$

where P stands for the volume fraction of the particles with dielectric constant ϵ_b embedded in the substrate characterized by the dielectric constant ϵ_a. In general, the solution to (9) is complex and we are only looking for continuous ϵ_2 with positive imaginary part.

III. Numerical results

Two types of composite substrates in a medium of dielectric constant $\epsilon_1 = 1.5$ are considered below:

A. Insulator/semiconductor substrate

The composite in this case is a semiconductor of dielectric function

$$\epsilon_a(\omega) = \epsilon_\infty + \frac{\omega_o^2}{\omega_1^2 - \omega^2 - i\Gamma\omega} \qquad (10)$$

containing small insulator particles with frequency independent dielectric constant[3] $\omega_b = 25$. In our numerical calculation, we have adopted the unit $\omega_o = 1$. Other parameters are $\omega_1 = 0.5$, $\Gamma = 0.08$, $\epsilon_\infty = 9$ and $\hat{d} = 0.5\ \omega$. The dependence of the rate γ of spontaneous decay on the frequency can be calculated from Eqs. (4), (7), (9) and (10). The results for various concentrations of small particles are plotted in Fig. 1.

It has been found that the curve peaks at a frequency corresponding to the minimum of the denominator of the integrand in Eq. (7). It may be of some interest to note from our numerical search that the denominator has only one minimum for each P value. It is known that such a resonant condition of the denominator determines the dispersion relation of the surface polariton.[12] If the polaritons do not decay, then the denominator vanishes, namely $\epsilon_1\mu_2 + \epsilon_2\mu_1 = 0$ for polaritons with infinite lifetime. That the minimum denominator remains finite in the present case is because the surface polariton decays. The origin of this damping is the absorption of the composite medium reflected in the imaginary part of the dielectric constant. Therefore the peak of the spontaneous decay rate is a consequence of the energy transfer from the excited admolecule to surface polaritons of the substrate. The curves in Fig. 1 clearly show that a larger concentration of insulator particles in the medium leads to less energy transfer or stronger damping of the surface polariton.

B. Metal/insulator substrate

We now consider an insulator with dielectric constant $\epsilon_a = 25$ and metallic particles distributed randomly throughout its volume. The dielectric function of the metal is

$$\epsilon_b(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega+i\Gamma_p)} \quad , \tag{11}$$

where ω_p is the plasma frequency and Γ_p the damping constant. We employ units such that $\omega_p = 1$ and take $\Gamma_p = 0.01$ and $\hat{d} = 0.5\omega$ in the following calculation. Numerical computations similar to the above case have been performed, with the results plotted in Fig. 2. It is observed here that the surface plasmon does not appear until the metallic concentration reaches a certain size. Thus there is no evident energy transfer for small P. According to our calculation, the surface plasmon starts to cause energy transfer when $P \gtrsim 0.6$, as can be seen from the peaks in Fig. 2.

We now turn our attention to the resonance fluorescence spectrum in this case. By making use of the regression theorem for correlation functions,[13] we find from the SBE the well-known results of the incoherent resonance fluorescence spectrum,[9,14]

$$\tilde{g}(\nu) = \frac{1}{2}\,|\Omega|^4\,\gamma[D^2 + \tfrac{1}{2}|\Omega|^2 + 4\gamma^2]/[(\tfrac{1}{2}|\Omega|^2 + |z|^2)(x^2 + y^2)] \quad , \tag{12}$$

where $D = \nu - \omega_L$, $x = 2\gamma(\frac{1}{2}|\Omega|^2 + |z|^2 - 2D^2)$, $y = D(|\Omega|^2 + |z|^2 + 4\gamma^2 - D^2)$ and $z = \gamma + i(\Delta+\Omega^s)$. The effects of the substrate are reflected through γ and Ω^s. We have found from our numerical study that both the height of the peaks and the position of the sidebands are sensitive to any change of the particle concentration P when the transition frequency of the admolecule is close to the surface plasmon frequency. The peaks in the spectrum diminish as P increases and eventually disappear when P becomes sufficiently large. Part of our numerical results is shown in Fig. 3. It is seen that the presence of the composite substrate does not change the nature of the spectrum. The ac Stark effect still splits each of the two molecular states equally into four levels, such that the resulting three-peak spectrum is symmetric with respect to the main transition frequency. The spacing between lines is affected by Ω^s while the line widths are influenced by γ^s. Of course, both Ω^s and γ^s depend on the nature of the substrate material.

References

1. R. K. Jain and R. C. Lind, J. Opt. Soc. Am. 73, 647 (1983).
2. P. Roussignol, D. Ricard, J. Lukasik and C. Flytzanis, J. Opt. Soc. Am. B 4, 5 (1987).
3. D. Stroud and Van E. Wood, J. Opt. Soc. Am. B 6, 778 (1989).
4. A. E. Neeves and M. H. Birnboim, J. Opt. Soc. Am. B 6, 787 (1989).
5. Y. Q. Li, C. C. Sung, R. Inguva and C. M. Bowden, J. Opt. Soc. Am. B 6, 814 (1989).
6. K. H. Drexhage, J. Lumin. 1-2, 693 (1970); Progress in Optics, Vol. XII (North-Holland, Amsterdam, 1974), p. 165 ff.
7. R. R. Chance, A. Prock and K. Silbey, Adv. Chem. Phys. 37, 1 (1978).
8. X. Y. Huang, J. T. Lin and T. F. George, J. Chem. Phys. 80, 893 (1984); H. Arnoldus and T. F. George, Phys. Rev. A 37, 761, 770 (1988); Y. S. Kim, P. T. Leung and T. F. George, Surf. Sci. 195, 1 (1988).
9. X. S. Li and C. D. Gong, Phys. Rev. A 35, 1595 (1987); B 39, 8284 (1989); B 39, 8283 (1989).
10. X. S. Li, D. L. Lin and T. F. George, Phys. Rev. B, submitted; in Atomic and Molecular Physics, ed. by M. S. Chaghtai (Aligarh Muslim University, Aligarh, India), in press.
11. D. A. G. Bruggeman, Ann. Phys. (Leipzig) 24, 636 (1935).
12. G. S. Agarwal, Phys. Rev. A 11, 230, 243, 253 (1975); 12, 1475 (1975).
13. M. Lax, Phys. Rev. 157, 213 (1967); 172, 172 (1968).
14. B. R. Mollow, Phys. Rev. 188, 1969 (1969).

Figure Captions

1. Decay rate γ vs frequency for dielectric particles embedded in a semiconductor. The volume fraction is $P = 0$ for the solid line, $P = 0.1$ for the dashed line, $P = 0.4$ for the dotted line, and $P = 1.0$ for the dot-dashed line.

2. Decay rate vs frequency for metal particles distributed in a dielectric medium. The volume fraction is $P = 1.0$ for the solid line, $P = 0.8$ for the dotted line, $P = 0.7$ for the dot-dashed line, and $P = 0.4$ for the dashed line.

3. Resonance fluorescence spectrum for a molecule near the surface of a bulk solid which is composed of a dielectric medium in which metal particles are randomly distributed, with $|\Omega| = 45.0$, $\Delta = -5.0$ and $\omega = 0.82$. The solid line is for $P = 0.4$, and the dot-dashed line is for $P = 0.7$.

Fig. 1

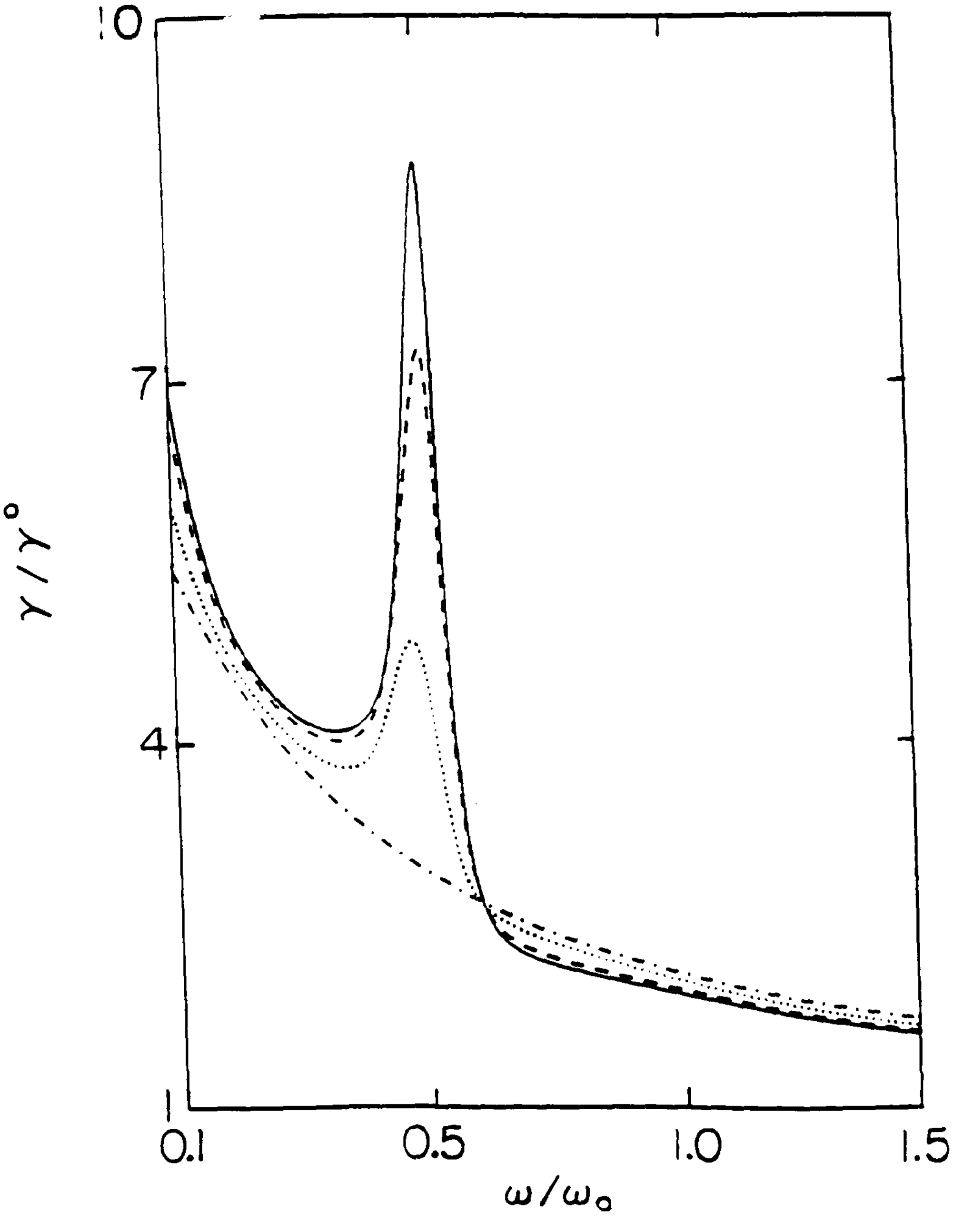


Fig. 2

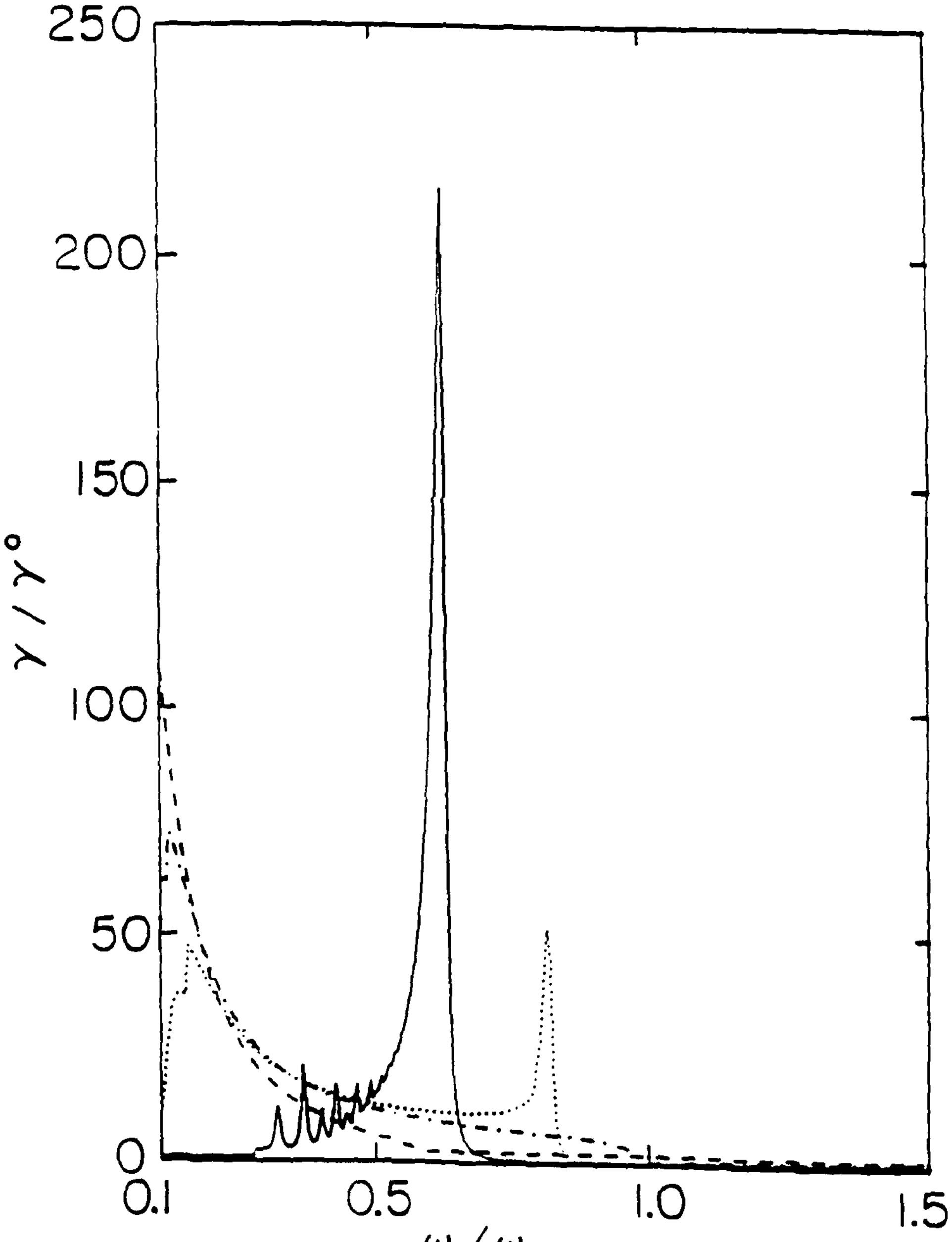
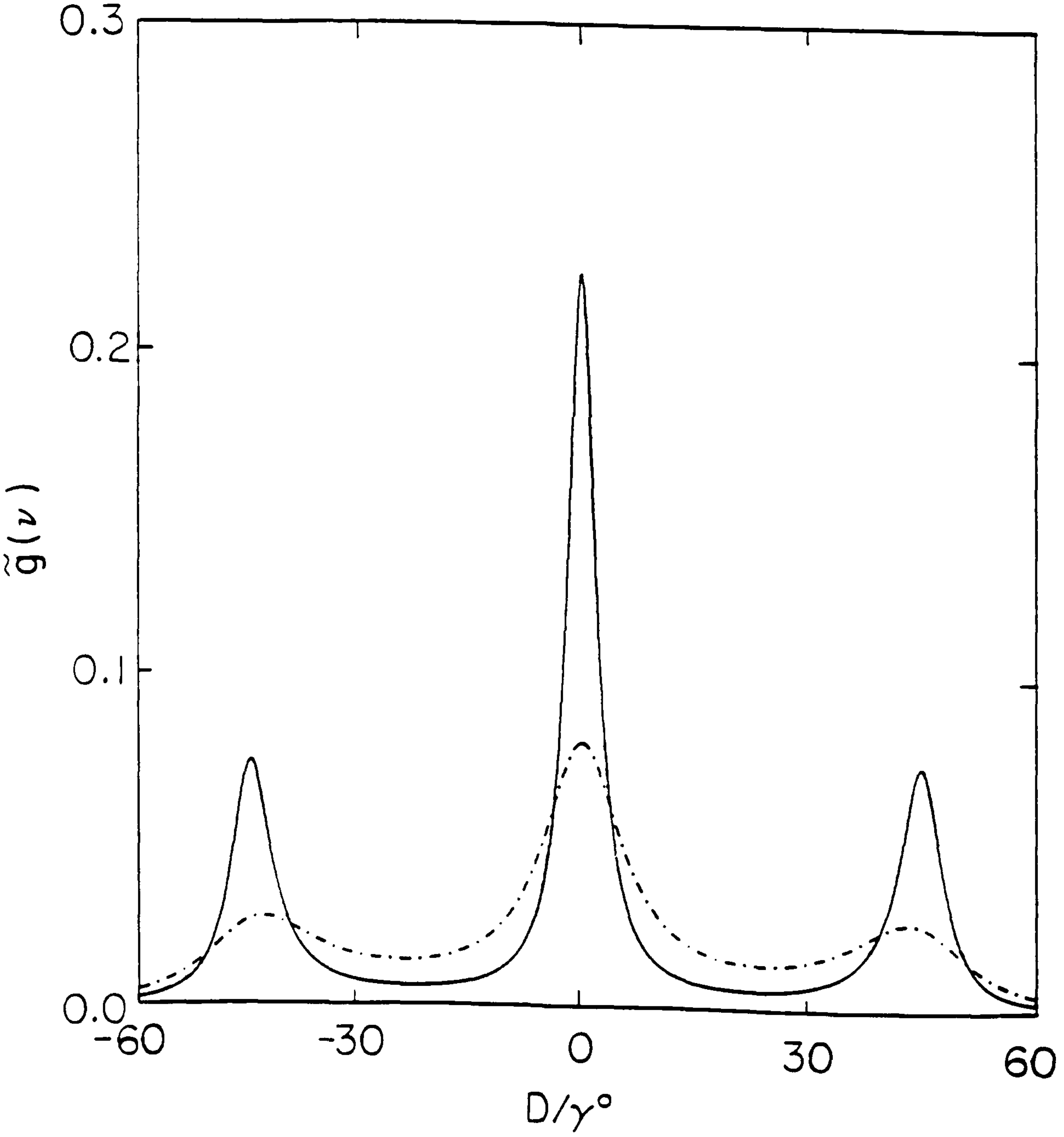


Fig. 3



DL/1113/86/2

TECHNICAL REPORT DISTRIBUTION LIST, GEN

	No. Copies
Office of Naval Research Attn: Code 1113 800 N. Quincy Street Arlington, Virginia 22217-5000	2
Dr. Bernard Douda Naval Weapons Support Center Code 50C Crane, Indiana 47522-5050	1
Naval Civil Engineering Laboratory Attn: Dr. R. W. Drisko, Code L52 Port Hueneme, California 93401	1
Defense Technical Information Center Building 5, Cameron Station Alexandria, Virginia 22314	12 high quality
DTNSRDC Attn: Dr. H. Singerman Applied Chemistry Division Annapolis, Maryland 21401	1
Dr. William Tolles Superintendent Chemistry Division, Code 6100 Naval Research Laboratory Washington, D.C. 20375-5000	1
Dr. David Young Code 334 NORDA NSTL, Mississippi 39529	1
Naval Weapons Center Attn: Dr. Ron Atkins 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

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. J. E. Jensen
Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, California 90265

Dr. J. H. Weaver
Department of Chemical Engineering
and Materials Science
University of Minnesota
Minneapolis, Minnesota 55455

Dr. A. Reisman
Microelectronics Center of North Carolina
Research Triangle Park, North Carolina
27709

Dr. M. Grunze
Laboratory for Surface Science and
Technology
University of Maine
Orono, Maine 04469

Dr. J. Butler
Naval Research Laboratory
Code 6115
Washington D.C. 20375-5000

Dr. L. Interante
Chemistry Department
Rensselaer Polytechnic Institute
Troy, New York 12181

Dr. Irvin Heard
Chemistry and Physics Department
Lincoln University
Lincoln University, Pennsylvania 19352

Dr. K.J. Klaubunde
Department of Chemistry
Kansas State University
Manhattan, Kansas 66506

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

Dr. F. Kutzler
Department of Chemistry
Box 5055
Tennessee Technological University
Cookesville, Tennessee 38501

Dr. D. DiLella
Chemistry Department
George Washington University
Washington D.C. 20052

Dr. R. Reeves
Chemistry Department
Renssaeler Polytechnic Institute
Troy, New York 12181

Dr. Steven M. George
Stanford University
Department of Chemistry
Stanford, CA 94305

Dr. Mark Johnson
Yale University
Department of Chemistry
New Haven, CT 06511-8118

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

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
Code 6170
Washington, D.C. 20375-5000

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

ABSTRACTS DISTRIBUTION LIST, 056/625/629

Dr. F. Carter
Code 6170
Naval Research Laboratory
Washington, D.C. 20375-5000

Dr. Richard Colton
Code 6170
Naval Research Laboratory
Washington, D.C. 20375-5000

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 6190
Naval Research Laboratory
Washington, D.C. 20375-5000

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

Dr. Richard Greene
Code 5230
Naval Research Laboratory
Washington, D.C. 20375-5000

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

Dr. K. C. Janda
University of Pittsburg
Chemistry Building
Pittsburg, PA 15260

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

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

Dr. Martin Fleischmann
Department of Chemistry
University of Southampton
Southampton 509 5NH
UNITED KINGDOM

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

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

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

Dr. W. Goddard
Department of Chemistry and Chemical
Engineering
California Institute of Technology
Pasadena, California 91125

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

Dr. J. Baldeschwieler
Department of Chemistry and
Chemical Engineering
California Institute of Technology
Pasadena, California 91125

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

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

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