Quasi-Diffusion Between Phonon and Roton Gases in Two- and
Three-Dimensional Liquid Helium

by
C. I. Um, C. W. Jun, H. J. Shin and Thomas F. George

Prepared for Publication
in
Journal of Low-Temperature Physics

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

July 1989

Reproduction in whole or in part is permitted for any purpose of the
United States Government.

This document has been approved for public release and sale;
it's distribution is unlimited.
Quasi-Diffusion Between Phonon and Roton Gases in Two- and Three-Dimensional Liquid Helium

Temperature variations of the quasi-diffusion constant and thermal diffusion ratio between phonon and roton gases in two- and three-dimensional liquid helium are evaluated explicitly through the scattering of phonons by rotons. The diffusion constants in both dimensions decrease exponentially over the whole temperature range, while the thermal diffusion ratios increase and then decrease as temperature increases in the range from -0.6 to -1.1 K.
Quasi-diffusion between phonon and roton gases in two- and three-dimensional liquid helium

Chung-In Um and Chul-Won Jun
Department of Physics
College of Science
Korea University
Seoul 136-701, Korea

Hyun-Joon Shin
Research Institute of Industrial Science and Technology
1 Gyedong-dong, Pohang City
Kyoungbuk 790-300, Korea

Thomas F. George
Departments of Chemistry and Physics
239 Fronczak Hall
State University of New York at Buffalo
Buffalo, New York 14260

Temperature variations of the quasi-diffusion constant and thermal diffusion ratio between phonon and roton gases in two- and three-dimensional liquid helium are evaluated explicitly through the scattering of phonons by rotons. The diffusion constants in both dimensions decrease exponentially over the whole temperature range, while the thermal diffusion ratios increase and then decrease as temperature increases in the range from $-0.6$ to $-1.1$ K.

PACS Nos.: 61.20.p, 66.10Cb, 67.40.Pm
1. Introduction

Since Landau's phenomenological theory of the superfluids, it is well known that liquid helium at low frequencies, long wavelengths and low temperatures can be described by Landau's two-fluid equations. These equations involve not only the normal and superfluid density and thermodynamic functions, but also the various sounds and transport kinetic coefficients in liquid $^3$He and $^4$He. Concerning the kinetic coefficients, Landau and Khalatnikov first investigated the thermal conductivity and viscosity, which were also studied later by others. Diffusive processes in liquid $^3$He and $^3$He-$^4$He mixtures have been extensively studied: Reuppeiner et al measured the thermal conductivity ($K$), thermal diffusion ratio ($K_T$) and mass diffusivity ($D$) as a function of $^3$He number concentration, and Behringer and Meyer investigated diffusive relaxation processes in the normal and superfluid phase in liquid $^3$He-$^4$He mixtures. All these quantities mentioned above are closely dependent on the elementary excitation, which is appropriate to describe the given Bose system. Motivated by these studies of $^3$He-$^4$He mixtures, in the present paper we evaluate the temperature dependence of the diffusion constant ($D$) and thermal diffusive ratio ($K_T$) between the phonon and roton gases in consideration of the scattering of phonons by rotons in two- and three-dimensional liquid $^4$He.

Recently we have obtained microscopically the Landau-type excitation spectrum, which is (anomalous) phonon-like at low momentum and roton-like for large momenta in the ring diagram approximation. Using this excitation spectrum we have successfully analyzed the sounds, sound attenuations, kinetic coefficients, etc., in two- and three-dimensional liquid $^4$He.

Through the calculations we can consider the excitation spectra in both dimensions:
\[ \mathcal{E}(p) - C_0 P[1 + \gamma P^2 - \delta P^4 + \ldots] \quad \text{(2D)} \quad (1.1) \]

\[ \mathcal{E}(p) - C_0 P[1 + \delta_1 P^2 - \delta_2 P^4 + \ldots] \quad \text{(3D)} \quad (1.2) \]

and

\[ \mathcal{E}(p) = \Delta + \frac{(P - P_0)^2}{2\mu} \quad \text{(2D and 3D)} \quad (1.3) \]

where \( P \) is the roton momentum, \( C_0 \) is the sound velocity, and \( \Delta, P_0 \) and \( \mu \) are the roton parameters (energy gap, momentum and effective mass, respectively). The subscript zero refers to \( T = 0 \) K. All coefficients in Eqs. (1.1) and (1.2) are positive, which are determined by the potential parameters. Here, we have adopted a soft potential with a Lennard-Jones type tail, which helps to make a smooth connection of the attractive part with the soft repulsive core. In the next section we evaluate the differential phonon-roton scattering cross section, and calculations of the diffusion constant and thermal diffusion ratio are described in Sec. 3. Finally, the results and discussion are presented in Sec. 4.

2. Phonon-roton differential scattering cross section

To obtain the two-dimensional phonon-roton scattering cross section, in this section we consider a roton in the presence of the phonon field. We can treat this roton as a particle in a moving liquid \(^4\)He. Then there appears an additional term \(-P \cdot \nu\), which can be written in symmetric form \(^{12}\)

\[ -\frac{1}{2}(\bar{P} \cdot \nu + \nu \cdot \bar{P}) \quad , \quad (2.1) \]
where \( \hat{P} \) and \( \hat{V} \) are the momentum and velocity operators. The phonon field changes the density of the medium, and thus we may expand the roton energy [Eq. (1.3)] in terms of the density \( \rho' \) to second order \( (\rho' - \rho - \rho_0) \) as

\[
H_r = H_{ro} + \frac{\partial}{\partial \rho} (\Delta + \frac{1}{2\mu} (P-P_0)^2) \rho' + \frac{1}{2!} \frac{\partial^2}{\partial \rho^2} (\Delta + \frac{1}{2\mu} (P-P_0)^2) \rho'^2 + \ldots ,
\]

(2.2)

where \( H_{ro} \) is given by Eq. (1.3). Since the value of most rotons is close to \( P_0 \), we may neglect \( (P-P_0) \) and replace \( P \) by \( P_0 \). We may also drop the term \( (\frac{\partial \Delta}{\partial \rho} \rho') \), which is much smaller than (2.1). Then the interaction energy between phonons and rotons can be written as

\[
\mathcal{V} = \frac{1}{2} (\hat{P} \cdot \hat{v} + \hat{v} \cdot \hat{P}) + \frac{1}{2} \left( \frac{\partial^2 \Delta}{\partial \rho^2} + \frac{1}{\mu} \frac{\partial^2 \Delta}{\partial \rho' \partial \rho} \right) \rho' .
\]

(2.3)

where the terms in the second bracket of Eq. (2.3) have magnitudes on the order of \( 10^{-1} \) to 1 in three-dimensional liquid helium.

When the roton changes momentum \( \hat{P} \) to \( \hat{P}' \), it absorbs a phonon with momentum \( \hat{p} \) and emits a phonon with momentum \( \hat{p}' \). Here we may consider two intermediate processes: (I) \( \hat{P} + \hat{p} \rightarrow \hat{P}' - \hat{p}' \) and (II) \( \hat{P} - \hat{p}' \rightarrow \hat{P}' - \hat{p}' + \hat{p} \). Since the roton momentum is much larger than that of the phonon, we may view this interaction as similar to that of heavy and light particles. The momentum and energy conservation law in collision processes can be written as

\[
cp + \frac{1}{2\mu} (P-P_0)^2 = cp' + \frac{1}{2\mu} (|\hat{P} + \hat{p} - \hat{p}'| - P_0)^2 .
\]

(2.4)
Under the conditions $p, p' \ll P_0$ and $E = cp \ll 3 \mu c^2$, Eq. (2.4) becomes

$$p - p' = \frac{1}{2\mu c P_0^2} (P_0 \hat{n} \cdot (p\hat{n} - p'\hat{n}'))^2$$

$$= \frac{P^2}{2\mu c} (\hat{n} \cdot (\hat{n} - \hat{n}'))^2,$$

(2.5)

where $\hat{n}$, $\hat{n}$ and $\hat{n}'$ are the unit vectors directed along $\hat{p}_0$, $\hat{p}$ and $\hat{p}'$, respectively. Therefore energy conservation implies $p = p'$. This means that particles do not change the magnitude of momentum, but change its direction. Taking account of $p, p' \ll P_0$ and $P = P_0$, the matrix element given in the differential cross section

$$d\sigma = \langle \Phi | H_3 | I \rangle^2 2 E_F - E_I \frac{d \vec{p}}{(2\pi)^2}$$

(2.6)

can be written in second-order perturbation as

$$\langle \Phi | H_3 | I \rangle = \frac{P_0 P}{2\rho_0} \left[ (\hat{n} \cdot \hat{n}) + (\hat{n} \cdot \hat{n}') \right] \frac{P_0}{\mu c} (\hat{n} \cdot \hat{n}')(\hat{n} \cdot \hat{n}')^2 + A \right),$$

(2.7)

$$A = \frac{P_0^2}{P_0 c} \left( \frac{\partial^2 A}{\partial \rho^2} + \frac{1}{\mu \partial \rho} \right)^2,$$

(2.8)

Substituting Eqs. (2.7)-(2.8) into Eq. (2.6) and performing the integration over $p'$, we obtain
Averaging Eq. (2.9) over all directions of roton momentum, we finally obtain

\[ d\sigma = \frac{P_0^2 P^3}{8\pi \hbar \rho_0 c^2} \left[ \frac{P_0^2}{\mu c} (\mu \cdot \hat{n})^2 (\mu \cdot \hat{n'})^2 + A^2 \right] d\theta . \]  

where \( \theta \) is the angle between the incident and scattered phonons.

Through the similar calculations we can obtain the differential scattering cross section of phonons by rotons in bulk liquid \(^4\)He: \(14\)

\[ d\sigma = \frac{P_0^2 P^3}{8\pi \hbar \rho_0 c^2} \left[ \frac{P_0^2}{\mu c} (\mu \cdot \hat{n})^2 (\mu \cdot \hat{n'})^2 + A^2 \right] d\theta . \]

where \( d\Omega \) is the solid angle.

3. Diffusion constant and thermal diffusion ratio

Since the excitation spectrum in liquid \(^4\)He consists of phonons and rotons, we may treat liquid \(^4\)He as a mixed phonon-roton gas. In the temperature range from \(-0.7\) to \(-1.2\) K, where the scattering of phonons by rotons is dominant, we consider the diffusion of phonons and rotons and also
the thermal diffusion ratio under the existence of a temperature gradient. There thermal processes in the mixture of a phonon-roton gas are very similar to those of light particles in heavy particles. Since the roton momentum is much larger than that of the phonon, we may treat the interactions between phonons and rotons as similar to those between light and heavy particles. Therefore, we may assume that when a collision occurs only between a phonon and roton, the roton is at rest and the phonon momentum changes only its direction with the same magnitude.

Let \( n_p \) and \( n_r \) be the number densities of the phonon and roton, respectively, and \( \theta \) the angle between the direction of a phonon with momentum \( \vec{p} \) and the x-axis. Equation (2.11) represent the differential scattering cross section that the momentum \( \vec{p} \) of a phonon will be changed to the momentum \( \vec{p}' \) directed into the solid angle element \( d\Omega \). The collision probability of a phonon per unit time becomes \( n_r c d\sigma \), where \( c \) is the phonon velocity. Let the number of phonons in a given unit volume with momentum between \( p \) and \( p + dp \) and directed into the solid angle \( d\Omega \) be \( n(p,\theta,x)d^3p \). Then the total number of phonons changing \( \vec{p} \) to \( \vec{p}' \) in \( d\Omega \) and conversely \( \vec{p}' \) to \( \vec{p} \) in \( d\Omega' \) are, respectively, given by

\[
d^3p \int n_r c n(p,\theta,x) \ d\sigma \ ,
\]

\[
d^3p \int n_r c n(p',\theta',x) \ d\sigma \ .
\]

The difference between the above two processes,

\[
d^3p \ n_r c \int [n(p',\theta',x) - n(p,\theta,x)] \ d\sigma \ .
\]
represents the change in the number of phonons in the volume element $d^3p$, which must be equal to the total time derivative of $n$:

$$J_{\text{phr}}(n) = c \cos \theta \frac{\partial n}{\partial x} = n_T c \int [n(c', \theta', x) - n(p, \theta, x)] \, d\sigma' \quad . \tag{3.4}$$

If the temperature and concentration gradients vary very slowly, we can express the phonon distribution function as

$$n = n_0(p, x) + \delta n(p, \theta, x) \quad , \tag{3.5}$$

where $\delta n$ is a small correction term to the equilibrium distribution function $n_0$. Now we assume that $\delta n$ is linear in the gradient of the concentration and temperature, and has the form

$$\delta n = \cos \theta f(p, x) \quad . \tag{3.6}$$

Substitution of Eq. (3.6) and $\cos \theta' = \cos \theta \cos \psi + \sin \theta \sin \psi \cos (\psi - \psi')$ in Eq. (3.4) and then integration over the solid angle yields

$$J_{\text{phr}}(n) = \cos \theta \, n_T c f(p, x) \frac{a_p^2 k_B^4 T^4}{4 \pi \hbar^4 \rho_0^6 \Gamma} \quad , \tag{3.7}$$

$$\Gamma = \frac{4}{45} + \frac{1}{25} \frac{P_0}{\mu c}^2 + \frac{2}{9} \frac{P_0^A}{\mu c} + \lambda_0^2 \quad .$$
Here we have made use of the relation $p = a k_B T/c$, where $a$ is a constant\(^{15}\) (see the Appendix). From Eqs. (3.4) and (3.7), we obtain the following expression for $f(p,x)$:

$$f(p,x) = - \frac{1}{n r a^4 P^2 k_B T^4} \frac{\partial n}{\partial x} .$$

(3.8)

The diffusion flux $i$ along the x-axis is

$$i = \int n c \cos \theta \, d^3 p = c \int \cos^2 \theta \, f(p,x) \, d^3 p .$$

(3.9)

Substituting Eq. (3.8) into Eq. (3.9) and integrating over momentum $p$ gives

$$i = \frac{4 \pi \hbar^4 \rho_0^2 c^7}{3 a^2 P^2 r k_B T^4} \frac{\partial n}{\partial x} .$$

(3.10)

Let the phonon concentration of the mixture be $n = n_p/(n_0 + n_r) = n_0/n$. Then the diffusion flux $i$ becomes

$$i = \frac{4 \pi \hbar^4 \rho_0^2 c^7}{3 a^2 P^2 r k_B T^4} n \frac{\partial n}{\partial x} + \eta \frac{\partial}{\partial x} \left( n \frac{\partial T}{\partial x} \right) .$$

(3.11)

Comparing Eq. (3.11) with the expression\(^{16}\) for the diffusion flux

$$i = -n D \left( \nabla_\eta + \frac{K_T}{T} \nabla T \right) .$$

(3.12)
we obtain

$$D = \frac{4\pi \rho_0 c^7}{3a P_0^2 \Gamma_n k_B^4}$$ \hspace{1cm} (3.13)

$$K_T = \eta T \frac{\partial}{\partial T} \ln(n)$$ \hspace{1cm} (3.14)

Since the number densities of phonons and rotons per unit volume can be given by

$$n_p = 2! \zeta(3) \frac{k_B^T}{2\pi^2 c^3} ,$$ \hspace{1cm} (3D) (3.15)

$$n_r = \frac{2P_0^2 (\mu k_B)^{1/2}}{(2\pi \hbar)^{3/2}} \frac{1}{t^{1/2}} e^{-\Delta/k_BT} ,$$ \hspace{1cm} (3.16)

we obtain the diffusion coefficient and thermal diffusion ratio of phonons in bulk liquid helium:

$$D(T) = \frac{(2\pi)^{5/2} \rho_0^2 (\hbar c)^7}{3a P_0^{1/2} \Gamma_n k_B^{3/2}} T^{-9/2} e^{\Delta/k_BT}$$ \hspace{1cm} (3.17)

$$K_T = \frac{3 + \frac{\zeta(3)}{\sqrt{2}} - 1 (\pi\mu)^{1/2} P_0^2 c^3 \left( 2 + \frac{\Delta}{k_BT} (k_BT)^{-5/2} e^{-\Delta/k_BT} \right)}{\left[ 1 + \frac{\zeta(3)}{\sqrt{2}} - 1 (\pi\mu)^{1/2} P_0^2 c^3 (k_BT)^{-5/2} e^{-\Delta/k_BT} \right]^2}$$ \hspace{1cm} (3.18)

Through similar calculations as done above, we obtain the diffusion coefficient and thermal diffusion ratio in thin helium films as
\[ D(T) = \frac{(2^5 \pi)^{1/2} P_0^2 \mu^5 c^6}{a^{1/2} P_0^3 \mu^1 T k_B^{7/2}} T^{-7/2} e^{-\Delta/k_B T} \]  

\[ K(T) = \frac{2 + (\zeta(2))^{-1} (2\pi \mu) P_0^2 \left( k_B T \right)^{-3/2} e^{-\Delta/k_B T}}{\left[ 1 + (\zeta(2))^{-1} (2\pi \mu) P_0^2 \left( k_B T \right)^{-3/2} e^{-\Delta/k_B T} \right]^2} \]

where we used the number densities of phonons and rotons per unit surface given by

\[ n_p = \frac{\zeta(2)}{2\pi} \left( \frac{k_B T}{\mu c} \right)^2 \]  

\[ n_r = \frac{P_0}{2\pi \mu^2} \left( 2\pi \mu k_B T \right)^{1/2} e^{-\Delta/k_B T} \]

and \( \Gamma' \) is given as

\[ \Gamma' = \frac{1}{4} + \frac{9}{32} \left( \frac{P_0}{\mu c} \right)^2 + \frac{P_0 A}{\mu c} + 2A^2 \]

4. Results and discussion

Since the elementary excitation spectrum in liquid helium consists of the combined phonon-roton gas, we may consider the diffusion of phonons into the roton gas, and also may include the thermal diffusion under the existence of the temperature gradient. We may treat the diffusion and thermal diffusion of the phonons in the roton gas as similar to those of light particles in heavy particle. For convenience we neglected phonon-phonon or roton-roton scatterings, permitting only phonon-roton scatterings.
The thermal diffusion ratio represents the ratio of the thermal diffusion coefficient due to the temperature gradient to the diffusion coefficient given by the concentration gradient. The diffusion coefficient must be positive, but the diffusion ratio may be positive or negative. The negative value of the coefficient $K_T$ means that the heavy particles will appear in the low-temperature region and the light particles in the high-temperature region. In $^3$He-$^4$He mixtures the ratio $K_T$ becomes negative near the plait point and positive near transition temperature. Since thermal diffusion ratios in our calculations are positive, phonons and rotons are located in the low- and high-temperature regions, respectively.

The diffusion constant and thermal diffusion ratios of the phonon gas in bulk liquid helium and in thin helium films are given by Eqs. (3.17)-(3.20). The potential and roton parameters are chosen by the analysis of the excitation spectrum for the bulk case and the specific data for the thin helium films (Table I). For the density variations of the roton parameters, we have adopted the results obtained by Khalatnikov, who analyzed the data of Dietrich et al. given by

$$\left(\frac{\rho^2}{\Delta}\right)(\frac{\partial \Delta}{\partial \rho}) = -1.142, \quad \left(\frac{\rho}{\Delta}\right)^2(\frac{\partial^2 \Delta}{\partial \rho^2}) = -2.06, \quad \left(\frac{\rho}{\rho_0}\right)(\frac{\partial \rho_0}{\partial \rho}) = \frac{1}{3}. $$

The above parameters in thin helium films are not known and thus are assumed to have the same values in the bulk case. The constants $a$ and $a'$ in Eqs. (3.7) and (3.19) can be determined by the calculation of the collision time for the phonon-roton scatterings, which characterize the thermal conductivity and viscosity. The numerical values of these $a$ and $a'$ are 6.28 and 4.67, respectively.
Figure 1 illustrates the diffusion constant $D$ as a function of temperature in the bulk and for films. As temperature increases, the roton density increases more rapidly than the phonon density. Therefore, the mean free path of phonons becomes shorter and the coefficient decreases rapidly.

The temperature variations of the coefficients $K_T$ are shown in Fig. 2. Below $-0.6$ K the coefficient is almost constant. In the temperature range from $-0.6$ to $-1.1$ K the coefficient ratio increases, which means that phonon-roton scatterings play a main role in the transport phenomena. This temperature range agrees well with the results obtained by Landau and Khalatnikov. For temperature far below $-0.6$ K, the phonon population is dominant, and thus phonon-phonon interactions becomes important, while roton-roton interactions and five-phonon processes will be dominant above $-1.1$ K.

In thin helium films the temperature range in which phonon-roton scatterings are effective and dominant becomes $-0.3 \, K < T < 0.8 \, K$. This range is in good agreement with the results obtained from the evaluation of kinetic coefficients in thin helium films. All arguments mentioned with respect to the bulk helium will be valid.

Acknowledgments

This work was supported by the Special Research Fund (SRF), Ministry of Science and Technology, Republic of Korea. Support was also received by the Office of Naval Research and the Air Force Office of Scientific Research (AFSC), United States Air Force, under Contract F49620-86-C-0009. The United States Government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright notation hereon.
Appendix

Making use of Eqs. (3.13)-(3.15), (3.21) and (All) from Ref. 15, we can easily obtain the characteristic time \( r^{-1}_{\text{ph-r}} \) expressed as a function of the phonon momentum and temperature, respectively, as

\[
r^{-1}_{\text{ph-r}} = N_r \frac{P_0^3}{8 \pi \rho_c} \left[ \frac{1}{4} + \frac{9}{32} \left( \frac{P_0}{\mu_c} \right)^2 + \frac{P_0}{\mu_c} A + 2A^2 \right], \tag{A1}
\]

and

\[
r^{-1}_{\text{ph-r}} = \frac{61\xi(6)}{31\xi(3)} N_r \frac{P_0^2 k_B T}{8 \pi 3 \rho_c} \left[ \frac{1}{4} + \frac{9}{32} \left( \frac{P_0}{\mu_c} \right)^2 + \frac{P_0}{\mu_c} A + 2A^2 \right]. \tag{A2}
\]

where \( N_r \) is the number of rotons per unit area. Setting (A1) equal to (A2), we get

\[
\rho_c = \frac{61\xi(6)}{31\xi(3)}^{1/3} k_B T. \tag{A3}
\]

Therefore, we obtain \( \nu' = 4.67 \) in two-dimensional liquid helium.

Through a similar calculation we can evaluate the characteristic time expressed by temperature and phonon momentum:

\[
r^{-1}_{\text{ph-r}} = 4\pi \rho_r \left( \frac{P_0^2}{4 \pi k_B \rho_c} \right)^2 \left[ \frac{4}{25} + \frac{1}{25} \left( \frac{P_0}{\mu_c} \right)^2 + \frac{2}{9} \left( \frac{P_0}{\mu_c} A \right) + 2A^2 \right]. \tag{A4}
\]

and
From Eqs. (A4)-(A5) we obtain $a = 2\pi$ in the bulk case.
References


Table I. Theoretical Parameters

<table>
<thead>
<tr>
<th></th>
<th>( \eta )</th>
<th>( \Delta/k_B \ (K) )</th>
<th>( q_0 \ (\text{Å}^{-1}) )</th>
<th>( \mu )</th>
<th>( C \ (\text{m/s}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D</td>
<td>( 2.18 \times 10^{-2} \ \text{Å}^{-3} )</td>
<td>8.616</td>
<td>1.930</td>
<td>0.153m(_{\text{He}})</td>
<td>238.21</td>
</tr>
<tr>
<td>2D</td>
<td>( 2.79 \times 10^{-2} \ \text{Å}^{-2} )</td>
<td>4.12</td>
<td>1.02</td>
<td>0.77m(_{\text{He}})</td>
<td>164.4</td>
</tr>
</tbody>
</table>
Figure Captions

1. Diffusion constants of phonons in the roton gas as a function of temperature. The solid and dotted lines represent the theoretical curves in two- and three dimensional liquid $^4\text{He}$.

2. Thermal diffusion ratio of phonons in the roton gas versus temperature. The solid and dotted lines represent the theoretical curves in two- and three-dimensional liquid $^4\text{He}$.
Fig. 2

The diagram shows the relationship between \( \log_{10} D(T) \) and \( T(K) \) for a certain system. The values range from \( 5.0 \) to \( -7.0 \) on the vertical axis and from \( 0.2 \) to \( 1.4 \) on the horizontal axis. The graph includes a solid line and a dashed line, indicating different data sets or conditions.
<table>
<thead>
<tr>
<th>No. Copies</th>
<th>No. Copies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Office of Naval Research</strong>&lt;br&gt;Attn: Code 1113&lt;br&gt;800 N. Quincy Street&lt;br&gt;Arlington, Virginia 22217-5000</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Dr. David Young&lt;br&gt;Code 334&lt;br&gt;NORDA&lt;br&gt;NSTL, Mississippi 39529</td>
</tr>
<tr>
<td>Dr. Bernard Doula&lt;br&gt;Naval Weapons Support Center&lt;br&gt;Code 50C&lt;br&gt;Crane, Indiana 47522-5050</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Naval Weapons Center&lt;br&gt;Attn: Dr. Ron Atkins&lt;br&gt;Chemistry Division&lt;br&gt;China Lake, California 93555</td>
</tr>
<tr>
<td>Naval Civil Engineering Laboratory&lt;br&gt;Attn: Dr. R. W. Drisko, Code LS2&lt;br&gt;Port Hueneme, California 93401</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Scientific Advisor&lt;br&gt;Commandant of the Marine Corps&lt;br&gt;Code RO-1&lt;br&gt;Washington, D.C. 20380</td>
</tr>
<tr>
<td>Defense Technical Information Center&lt;br&gt;Building 5, Cameron Station&lt;br&gt;Alexandria, Virginia 22314</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>U.S. Army Research Office&lt;br&gt;Attn: CRD-AA-IP&lt;br&gt;P.O. Box 12211&lt;br&gt;Research Triangle Park, NC 27709</td>
</tr>
<tr>
<td>DTNSRDC&lt;br&gt;Attn: Dr. H. Singerman&lt;br&gt;Applied Chemistry Division&lt;br&gt;Annapolis, Maryland 21401</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Mr. John Boyle&lt;br&gt;Materials Branch&lt;br&gt;Naval Ship Engineering Center&lt;br&gt;Philadelphia, Pennsylvania 19112</td>
</tr>
<tr>
<td>Dr. William Tolles&lt;br&gt;Superintendent&lt;br&gt;Chemistry Division, Code 6100&lt;br&gt;Naval Research Laboratory&lt;br&gt;Washington, D.C. 20375-5000</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Naval Ocean Systems Center&lt;br&gt;Attn: Dr. S. Yamamoto&lt;br&gt;Marine Sciences Division&lt;br&gt;San Diego, California 91232</td>
</tr>
<tr>
<td></td>
<td>Dr. David L. Nelson&lt;br&gt;Chemistry Division&lt;br&gt;Office of Naval Research&lt;br&gt;800 North Quincy Street&lt;br&gt;Arlington, Virginia 22217</td>
</tr>
</tbody>
</table>
ABSTRACTS DISTRIBUTION LIST, 056/625/629

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Dr. K.J. Klaubunde
Department of Chemistry
Kansas State University
Manhattan, Kansas 66506
ABSTRACTS DISTRIBUTION LIST, 056/625/629

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

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

Dr. J. Murday
Naval Research Laboratory
Code 6170
Washington, D.C. 20375-5000

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

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

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

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

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

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

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

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

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

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

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

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

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

Dr. O. E. Harrison
Department of Physics
Naval Postgraduate School
Monterey, California 93940
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 Pittsburgh  
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. J. T. Keiser
Department of Chemistry
University of Richmond
Richmond, Virginia 23173

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

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

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

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

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

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

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

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

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

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

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

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

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