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OFFICE OF NAVAL RESEARCH

Contract N00014-86-K-0043

TECHNICAL REPORT No. 71

The coefficient of first viscosity via three-phonon processes in bulk liquid helium

by

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Prepared for Publication

in

Physical Review B

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

June 1988

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

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/88/TR-71

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
Contract N00014-86-K-0043

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)*
The coefficient of first viscosity via three-phonon processes in bulk liquid helium

12. PERSONAL AUTHOR(S)
C. I. Um, C. W. Jun, W. H. Kahng and Thomas F. George

13a. TYPE OF REPORT

13b. TIME COVERED
FROM ________ TO ______

14. DATE OF REPORT *(Year, Month, Day)*
June 1988

15. PAGE COUNT
15

16. SUPPLEMENTARY NOTATION
Prepared for publication in Physical Review B

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
BULK LIQUID HELIUM, THEORETICAL STUDY
FIRST VISCOSITY, INVERSE TEMEPRATURE DEPENDENCE,
COEFFICIENT THREE-PHONON PROCESSES.

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

The contribution of three-phonon processes to the coefficient of first viscosity in bulk liquid helium is evaluated explicitly as a function of temperature, which is shown to have a T^{-1} dependence.

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

DD Form 1473, JUN 86 *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

Physical Review B, in press

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PACS NO. 05.60 +W, 66.20.+d, 67.40 Pm.

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1. Introduction

Since Landau and Khalatnikov's work[1] on transport coefficients, i.e., the thermal conductivity and viscosities of liquid helium, Khalatnikov and Matveev[2] reexamined the transport coefficients due to contributions by phonon-roton scattering and noted that the results of Landau and Khalatnikov's work with a normal dispersion deviate from experimental data by as much as a factor of two. The correct anomalous dispersion indicates three-phonon processes (3PP) to be important near absolute zero temperature, and should thus be included in calculations of transport kinetic coefficients.

It is well known that the kinetic equation with temperature gradient for the thermal conductivity vanishes for a pure phonon gas, and thus the corresponding thermal conductivity becomes zero. However, the kinetic equation for the first viscosity does not vanish for a pure phonon gas near zero temperature, and 3PP become important. The purpose of this paper is to evaluate the contribution to the coefficient η_{ph} of first viscosity from 3PP which were not included in the work of Landau and Khalatnikov. For small momenta the three-dimensional dispersion relation has been evaluated explicitly by adopting a soft potential to give[3]

$$\epsilon(p) = C_o p[1 + \gamma p^2 - \delta p^3 + \ldots] \quad , \qquad (1.1)$$

where C_o is the velocity of sound at absolute zero temperature. For bulk liquid helium of density 2.18×10^{-2} Å^{-3}, we can use the following values[4] obtained to fit the experimental data[5] of the excitation energy spectrum:

$$\gamma\hbar^2 = 1.51\text{Å}^2,\ \delta\hbar^3 = 3.25\text{Å}^3,\ C_o = 238.2\ \text{m/s},\ u = 1.8\ ^{6)} \quad .$$

In Sec. 2 we consider phonon-phonon interactions in bulk liquid helium via second quantization to obtain the characteristic time for 3PP. We then solve the kinetic equation for the coefficient of first viscosity in Sec. 3. Finally, in Sec. 4 we discuss numerical results.

2. Phonon-phonon interaction in a three-dimensional quantum liquid

To consider the phonon-phonon interaction in a three-dimensional quantum liquid, we begin with the Hamiltonian H and the internal energy $E(\rho)^{7)}$ for superfluid liquid ^{4}He, given by

$$H = \int d^3r \, [\tfrac{1}{2}\hat{v}\cdot\hat{\rho}\hat{v} + E(\rho)] \quad , \qquad (2.1)$$

$$E(\rho) = E(\rho_o) + \int d^3p \; n\epsilon(p) \quad , \qquad (2.2)$$

where $\hat{v}$ and $\hat{\rho}$ are the velocity and density operators expressed in terms of the annihilation operator $\hat{a}_p$ and creation operator $\hat{a}_p^\dagger$, n is the number density of excitations, and $\hat{\rho}$ is given by $\hat{\rho}_o + \hat{\rho}'$, the constant and variable parts, respectively. Expanding the internal energy $E(\rho)$ as a function of ρ' and then expressing this expansion in terms of annihilation and creation operators, we obtain

$$H = H_0 + H_3 + H_4 + \ldots \qquad (2.3)$$

$$H_0 = \sum_p (\hat{a}_p^\dagger \hat{a}_p + \tfrac{1}{2})\hbar\omega \quad ,$$

$$H_3 = 4\pi^3 i\left(\frac{\hbar}{2V}\right)^{3/2} \sum_{p_1} \sum_{p_2} \sum_{p_3} \left[\left(\frac{C_o p_3}{\rho_o p_1 p_2}\right)^{1/2} (\vec{p}_1 \cdot \vec{p}_2) + \frac{\rho_o^2}{3C_o^2} \frac{\partial}{\partial\rho}\left(\frac{C_o}{\rho}\right)^2\right.$$

$$\left. \times \left(\frac{C_o p_1 p_2 p_3}{\rho_o}\right)^{1/2}\right] [\hat{a}_{p_1} \hat{a}_{p_2} \hat{a}_{p_3} \delta(\vec{p}_1 + \vec{p}_2 + \vec{p}_3) \exp(-i(\omega_1 + \omega_2 + \omega_3)t)$$

$$+ \hat{a}_{p_1} \hat{a}^\dagger_{p_2} \hat{a}_{p_3} \delta(\vec{p}_1 - \vec{p}_2 - \vec{p}_3) \exp(-i(\omega_1 - \omega_2 - \omega_3)t) + \dots) \quad , \qquad (2.4)$$

$$H_4 = \frac{(2\pi)^3}{4!} \left(\frac{\rho_o \hbar}{2VC_o}\right)^2 \frac{\partial^2}{\partial\rho^2} \left(\frac{C_o^2}{\rho}\right) \sum_{p_1} \sum_{p_2} \sum_{p_3} \sum_{p_4} (p_1 p_2 p_3 p_4)^{1/2}$$

$$\times [\hat{a}_{p_1} \hat{a}_{p_2} \hat{a}_{p_3} \hat{a}_{p_4} \; \delta(\vec{p}_1 + \vec{p}_2 + \vec{p}_3 + \vec{p}_4) \exp(-i(\omega_1 + \omega_2 + \omega_3 + \omega_4)t)$$

$$+ \hat{a}_{p_1} \hat{a}^\dagger_{p_2} \hat{a}^\dagger_{p_3} \hat{a}_{p_4} \delta(\vec{p}_1 - \vec{p}_2 - \vec{p}_3 + \vec{p}_4) \exp(-i(\omega_1 - \omega_2 - \omega_3 + \omega_4)t) + \dots] \quad , (2.5)$$

where the other six terms to be included in Eq. (2.4) are given by combinations of $\hat{a}_{p_1}, \hat{a}_{p_2}, \hat{a}_{p_3}$ and $\hat{a}^\dagger_{p_1}$, $\hat{a}^\dagger_{p_2}$, $\hat{a}^\dagger_{p_3}$, and fourteen additional terms with the combinations of four creation and four annihilation operators appear in Eq. (2.5).

The nonzero matrix elements of $\hat{a}_p$ and $\hat{a}^\dagger_p$ are

$$\langle n_p - 1 | \hat{a}_p | n_p \rangle = -i(n_p)^{1/2} e^{i\omega t} \quad ,$$

$$\langle n_p | \hat{a}^\dagger_p | n_{p-1} \rangle = i(n_p)^{1/2} e^{-i\omega t} \quad . \qquad (2.6)$$

The matrix element $<n_p|H_0|n_p>$ is $\sum_p (n_p+\frac{1}{2})\hbar\omega$, where $\omega = c_o\rho$ and H_0 is thus the Hamiltonian of a simple harmonic oscillator. H_3 and H_4 are the anharmonic perturbative Hamiltonians. Transitions between different states occur due to H_3, H_4 and other higher-order perturbed Hamiltonians. The transition matrix element from state $|i>$ to state $|f>$ in second-order perturbation theory is given by

$$<f|H|i> = <f|H_3|i> + <f|H_4|i> + \sum_j \frac{<f|H_3|j><j|H_4|i>}{E_j - E_i} . \qquad (2.7)$$

According to Eqs. (2.6) and (2.4), the first term in Eq. (2.7) contributes only to 3PP, and the second and third terms are related to 4PP.

A finite lifetime of an elementary excitation in a quantum liquid originates from two processes. One is the collision between elementary excitations, and the other is the spontaneous decay of a phonon into two, three or more phonons. Since the collision probablity tends to zero at very low temperatures, the collision process will become less important and negligible. At very low temeperatures, below 0.6 K, the main excitations in liquid ^{4}He are phonons. Therefore, we may consider the decay of the phonon into two phonons only, i.e., 3PP,[8)] consisting of two processes: the direct process of emission of a phonon, $\vec{p}_3$, $\vec{p}_1 = \vec{p}_2 + \vec{p}_3$, and the reverse process of absorption of a phonon, $\vec{p}_3$, $\vec{p}_2 + \vec{p}_3 = \vec{p}_1$. The differential decay probability per unit time in three dimensions is given by

$$d\omega = \frac{2\pi}{\hbar} |<f|H_3|i>|^2 \delta(\epsilon_f - \epsilon_i) \frac{V^2 d\vec{p}_2 d\vec{p}}{(2\pi\hbar)^6} . \qquad (2.8)$$

Since the matrix elements in both processes are given by

$$<f|H_3|i>_D = \frac{3!}{2}\frac{(2\pi\hbar)^3}{(2V)^{3/2}}\delta(\vec{p}_1-\vec{p}_2-\vec{p})\{(\frac{C_o}{\rho_o}\frac{p}{p_1p_2})^{1/2}(\vec{p}_1\cdot\vec{p}_2)$$

$$+\frac{\rho_o{}^2}{3C_o{}^2}\frac{\partial}{\partial\rho}(\frac{C_o^2}{\rho})(\frac{C_op_1p_2p}{\rho_o})^{1/2}\}\sqrt{n_{p_1}(n_{p_2}+1)(n_p+1)}\quad , \tag{2.9}$$

$$<f|H_3|i>_R = \frac{3!}{2}\frac{(2\pi\hbar)^3}{(2V)^{3/2}}\delta(\vec{p}_1-\vec{p}_2-\vec{p})\{(\frac{C_o}{\rho_o}\frac{p}{p_1p_2})^{1/2}\ (\vec{p}_1\cdot\vec{p}_2)$$

$$+\frac{\rho_o{}^2}{3C_o{}^2}\frac{\partial}{\partial\rho}(\frac{C_o^2}{\rho})(\frac{C_op_1p_2p}{\rho_o})^{1/2}\}\ \sqrt{(n_{p_1}+1)n_{p_2}n_p}\quad , \tag{2.10}$$

where n_p is the distribution function of phonons with momentum p, the total decay probabilities per unit time of the two processes are

$$\omega_D = \frac{\pi C_o}{2\hbar\rho_o}(u+1)^2\int\frac{d\vec{p}_2}{(2\pi\hbar)^3}\,p_1p_2pn_{p_1}(n_{p_2}+1)(n_p+1)\delta(\epsilon_f-\epsilon_i)\quad , \tag{2.11}$$

$$\omega_R = \frac{\pi C_o}{2\hbar\rho_o}(u+1)^2\int\frac{d\vec{p}_2}{(2\pi\hbar)^3}\,p_1p_2p(n_{p_1}+1)n_{p_2}n_p\delta(\epsilon_f-\epsilon_i)\quad , \tag{2.12}$$

where u is the Grüneisen constant given by $(\rho_o/C_o)(\partial C_o/\partial\rho_o)$.

The collision integral, which is the difference between the differential decay probability per unit time for the direct and reverse processes, can be written as

$$J_{3PP} = -\frac{\pi C_o}{2\hbar\rho_o}(u+1)^2\int\frac{d\vec{p}_2}{(2\pi\hbar)^3}\,p_1p_2p\,\delta n(n_{p_{1_o}}-n_{p_{2_o}})\delta(\epsilon_f-\epsilon_i) \quad . \tag{2.13}$$

where $\delta n = n_p - n_{p_o}$, with n_{p_o} as the distribution function of phonons with momentum p in the equilibrium state. Since the collision integral $J_{3PP}(n)$ is given by $-(n-n_o)/\tau_{3PP}$, we have

$$\tau_{3PP}^{-1} = \frac{\pi C_o}{2\hbar\rho_o}(u+1)^2\int\frac{d\vec{p}_2}{(2\pi\hbar)^3}\,p_1p_2p(n_{p_{1_o}}-n_{p_{2_o}})\delta(\epsilon_f-\epsilon_i) \quad . \tag{2.14}$$

The three-phonon processes are small-angle processes, and thus p_1 and p_2 are much larger than p_3. Hence we may use the following relations to evaluate Eq. (2.14):

$$n_{p_{1_o}} - n_{p_{2_o}} = \left(\frac{\partial n_{p_{1_o}}}{\partial\omega_1}\right)\omega \quad , \tag{2.15}$$

$$\omega_2 - \omega_1 \simeq -\left(\frac{\partial\omega_1}{\partial p_1}\right)p_3 = -\omega\cos\theta \quad . \tag{2.16}$$

Substitution of Eqs. (2.15)-(2.16) into Eq. (2.14) and integration of Eq. (2.14) over momentum space yields

$$\frac{1}{\tau_{3PP}} = \omega\frac{\pi^3(u+1)^2k_B^4T^4}{30\hbar^3\rho_oC_o^5}\left[1-\frac{60\pi^2}{7}\gamma\left(\frac{k_BT}{C_o}\right)^2\right] \quad . \tag{2.17}$$

3. **Viscosity**

In this section we shall evaluate the coefficient of first viscosity. We first consider the macroscopic motion of liquid helium, which does not depend on time, with velocity $\vec{v}$ in the z-direction and the gradient directed along x-axis. Then the kinetic equation becomes

$$\vec{v}\cdot\vec{\nabla}n = v_x \frac{\partial n}{\partial x} = J(n) \quad . \tag{3.1}$$

The phonon distribution function in the motion of liquid helium with velocity $\vec{v}$ is given by

$$n_o = [\exp(\frac{Cp-\vec{v}\cdot\vec{p}}{k_B T}) - 1]^{-1} \quad , \tag{3.2}$$

where C is the phonon velocity (equal to C_o at zero temperature). Substitution of Eq. (3.2) into (3.1) yields

$$n_o(n_o+1)\frac{Cp}{k_B T}\frac{\partial v}{\partial x} \cos\theta\sin\theta\cos\phi = J(n) \quad , \tag{3.3}$$

where here θ is the angle between $\vec{p}$ and the z-axis. Since 4PP establish energy in the equilibrium state and the distribution function of phonons is related to the variation of phonons, which characterize the chemical potential α, the distribution function becomes

$$n = [\exp(\alpha' + \frac{pC}{k_B T} - 1)]^{-1} \quad . \tag{3.4}$$

Expanding Eq. (3.4) as a function of α' to obtain the deviation of n from n_o and considering the linearity of the left-hand side in Eq. (3.3), we can write

$$\delta n = n - n_o = - n_o(n_o+1)\alpha' \quad , \tag{3.5}$$

$$\alpha' = \alpha\cos\theta\sin\theta\cos\phi \quad . \tag{3.6}$$

Replacing J(n) by $J_{3PP}(n)$ in Eq. (3.3) and integrating over momentum space, we obtain

$$\int dp\ p^2\ J_{3PP}(n) = \cos\theta\sin\theta\cos\phi\left(\frac{k_BT}{C_o}\right)^3\ 3!\ \zeta(3)\frac{\partial v}{\partial x} \quad . \tag{3.7}$$

Since the collision integral $J_{3PP}(n)$ can be replaced by $-(n-n_o)/\tau_{3PP}$, we can use Eqs. (3.5)-(3.6) together with Eq. (2.17) and $\omega = pC_o/\hbar$ for the evaluation of collision integral:

$$\int dp\ p^2\ J_{3PP}(n) = \frac{\pi^3(u+1)^2(k_BT)^4}{30\hbar^4\rho_oC_o^{\ 4}}\left(\frac{k_BT}{C_o}\right)^4\ 3!\zeta(3)\ \alpha\ \cos\theta\sin\theta\cos\phi \quad . \tag{3.8}$$

From comparison of Eqs. (3.7) and (3.8) we have

$$\alpha = \frac{30\hbar^4\rho_oC_o^5}{\pi^3(u+1)^2(k_BT)^5}\frac{\partial v}{\partial x} = A\frac{\partial v}{\partial x} \quad . \tag{3.9}$$

The coefficient of first viscosity is obtained from the evaluation of the stress tensor associated with 3PP given by

$$\sigma_{xz} = -\eta_{ph}\frac{\partial v}{\partial x} = \int \frac{d\vec{p}}{(2\pi\hbar)^3} p_z v_x (n-n_o)$$

$$= \int dp \frac{p^2 \sin\theta d\theta d\phi}{(2\pi\hbar)^3} p \cos\theta \; C_o \sin\theta\cos\phi[-n_o(n_o+1)A\frac{\partial v}{\partial x}\cos\theta\sin\theta\cos\phi] \quad . \tag{3.10}$$

Performing the integral, Eq. (3.10) becomes

$$\sigma_{xz} = -\frac{3!\zeta(3)}{30\pi^2\hbar^3}\frac{(k_B T)^4}{C_o{}^3}A\frac{\partial v}{\partial x} \quad . \tag{3.11}$$

We can get the coefficient of first viscosity by comparing Eq. (3.11) with the first expression in Eq. (3.10):

$$\eta_{ph}(T) = \frac{3!\zeta(3)\hbar\rho_o C_o^2}{\pi^5 k_B (u+1)^2}\frac{1}{T} = 1.904 \times 10^{-7}\frac{1}{T} \quad . \tag{3.12}$$

We note that the coefficient of first viscosity1),9) at temperatures below 0.9 K is given by

$$\eta_{ph}(T) = 3.50 \times 10^{-9}\, T^{-1/2}\, e^{\Delta/k_B T}(1 + 2.15 \times 10^{-5} T^{9/2} e^{\Delta/k_B T})^{-1} \quad , T < 0.9 \text{ K} \quad . \tag{3.13}$$

4. Numerical Results and discussion

In previous sections we have evaluated the lifetime and the contribution of first viscosity. At relatively low temperatures (< 0.9 K), Eq. (3.13) reduces approximately to

$$\eta_{ph} \sim 1.5 \times 10^{-4} \frac{1}{T^5} .$$

However, as the temperature approaches absolute zero, the roton density becomes zero, and thus the contribution from the roton-phonon scattering to viscosity will vanish so that the main contribution comes from the 3PP. Therefore, the temperature dependence is changed from T^{-5} to T^{-1}. Figure 1 illustrates the coefficient $\eta_{ph}(T)$ given by Eq. (3.12). The coefficient increases slowly, and near zero temperature it increases very rapidly and finally diverges. In conclusion, we point out that in consideration of the 3PP originating from the anomalous excitation spectrum at low momenta, the temperature variation of first viscosity depends on T^{-1}.

Acknowledgments

The authors are very thankful to Professor J. S. Kang for a critical reading of the manuscript. This research was supported in part by a grant to Korea University from KOSEF under Contract No. 862-0203-011-2, and in part by the Office of Naval Research and Air Force Office of Scientific Research (AFSC), under Contract F49620-86-C-0009, with the Research Foundation of the State University of New York. The United States Government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright notation hereon.

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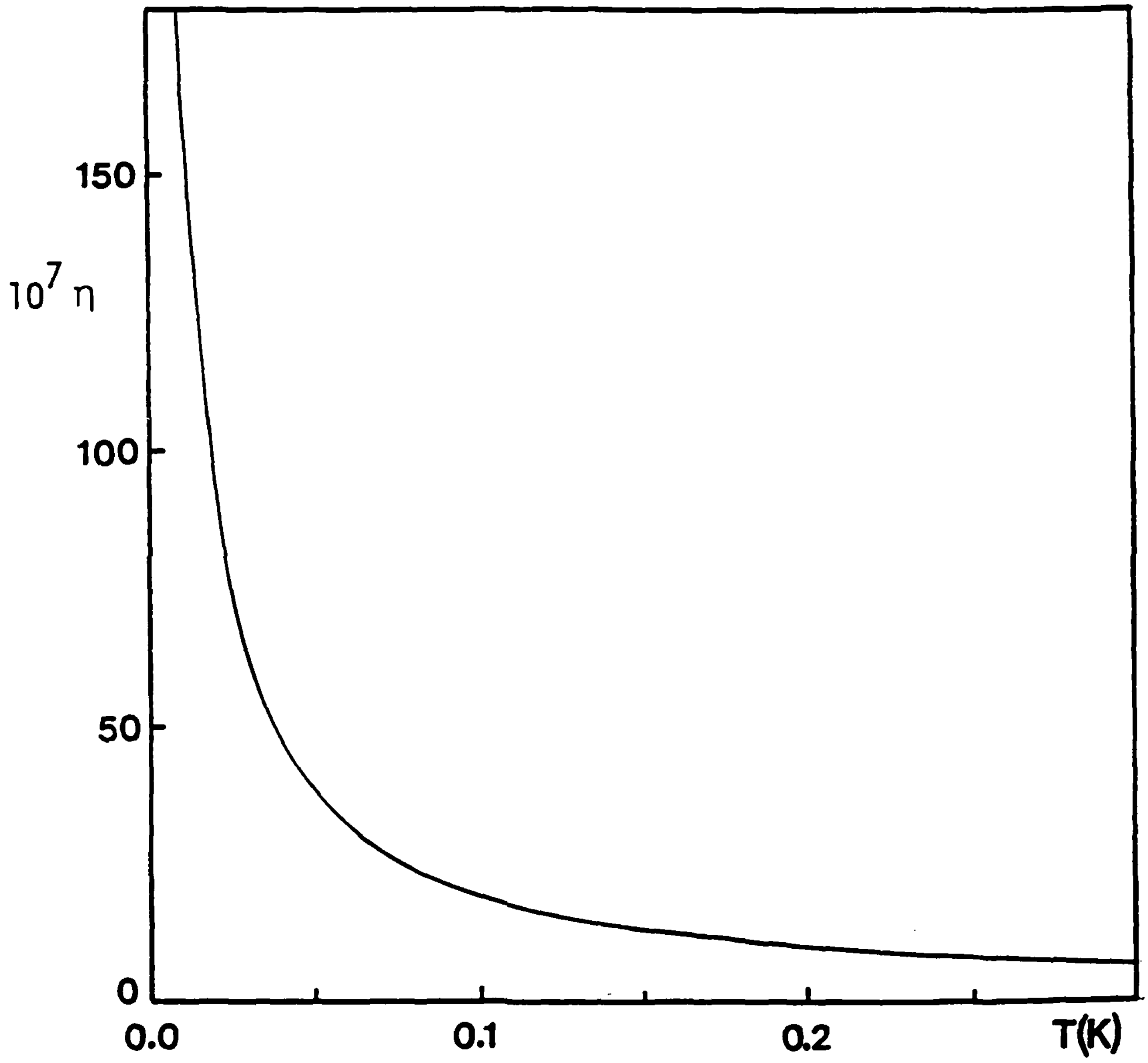
Figure Caption

Figure 1. Viscosity coefficient due to the contribution from 3PP.

Fig. 1



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