ABSORPTION STUDIES
of
METASTABLE HELIUM ATOMS

By

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Abstract

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The processes which destroy the metastable states of helium atoms have been studied by measuring the density of atoms in the various states as a function of time in the afterglow of a pulsed discharge. The density was determined by studying the time-varying optical absorption caused by the metastables. Various destruction processes have been postulated. By matching the experimental decay curves to the theoretical form of the decay, the coefficients for individual destruction processes were determined. In particular, the coefficients for destruction of $1s2s\,^3S_1$ metastable atoms resulting from collisions between two metastables and the coefficient for diffusion have been determined as a function of temperature. The diffusion coefficient at $300^{\circ}K$ is

$1.6 \times 10^{19} \left(\frac{cm^2}{sec}\right)\left(\frac{atoms}{cc}\right)$, and the metastable metastable destruction coefficient at 300°K is $7.3 \times 10^{-10} \left(\frac{cc}{atom}\right)\left(\frac{1}{sec}\right)$.

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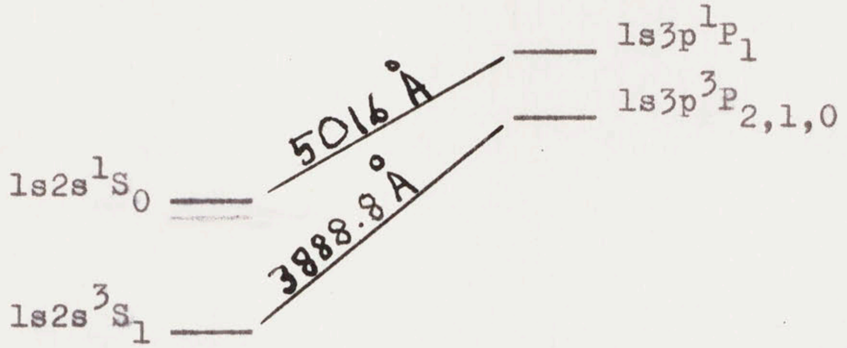
* This work was supported in part by the U.S. Army, the Air Force Office of Scientific Research, and the Office of Naval Research.

Introduction

The energy level diagram governing the states which we studied is the following:



Each metastable atom absorbs a photon of characteristic energy as it is raised to a higher excited state. Thus the fractional absorption by the gas of the 5016Å line of a helium light source yields information about the density of atoms in the singlet ^1S metastable state in the gas.

The theory for this type of experiment has been worked out in detail in references 2, 4, and 5; and only the results need be presented here. The equation found to govern the singlet ^1S metastable density N_s is:

$$\frac{\partial N_s}{\partial t} = D_s \nabla^2 N_s - A N_n N_s - \beta n N_s$$

The first term on the right side of this equation represents the loss of metastables due to diffusion where D_s is the diffusion coefficient. The second term represents the loss due to collisions between metastables and neutral atoms where N_n is the density of neutrals and A is the coefficient for the process. The last term represents loss due to superelastic collisions with electrons where n is the electron density and β is the coefficient. The equation may be separated and the solution to the time dependent part is (provided n is constant):

$$N_s = N_{s_0} e^{-\nu_s t} \quad \text{where} \quad \nu_s = \frac{D_s}{\Lambda^2} + A N_n + \beta n$$

Λ^2 is the diffusion length. For a cylindrical absorption cell of length L and radius R this is given by:

$$\frac{1}{\Lambda^2} = \left(\frac{\pi}{L}\right)^2 + \left(\frac{2.4}{R}\right)^2$$

ν_s is the destruction frequency.

The result for the triplet ^3S metastable density N_t is the following:

$$\frac{\partial N_t}{\partial t} = D_t \nabla^2 N_t - B N_n^2 N_t + \beta n N_s - 2 C N_t^2$$

D_t is the diffusion coefficient. The second term on the right represents the loss of metastables due to collisions with two neutral atoms, and B is the coefficient for the process. The third indicates the result due to Phelps[4] that the destruction of a singlet upon collision with an electron yields a triplet. The last represents loss due to collision of two metastables, and C is the coefficient. When the term $2CN_t^2$ is negligible, the solution is:

$$N_t = N_{t_1} e^{-\nu_t t} - N_{t_2} e^{-\nu_s t} \quad \text{where} \quad \nu_t = \frac{D_t}{\Lambda^2} + BN_n^2$$

We have attempted in our experiment to determine the coefficients D_s, β , D_t, and C as functions of temperature.

The output of our apparatus is a number proportional to absorption in the cell. Calibration is accomplished by observing the fractional absorption directly on an oscilloscope. The absorption in this type of experiment is given by Mitchell and Zemansky[1] as:

$$A_0 = \frac{k_0 L}{\sqrt{1+\alpha^2}} - \frac{(k_0 L)^2}{2!\sqrt{1+2\alpha^2}} + \cdots + \frac{(-1)^n (k_0 L)^n}{n!\sqrt{1+n\alpha^2}} + \cdots$$

where L is the length of the absorption cell, k_0 is proportional to the metastable density, and α is the ratio of the emission line breadth to the absorption line breadth. In appendix B it is shown that Doppler broadening of the lines is the only type that need be considered.

The Doppler broadening is found to be:

$${}^3P_{2,1,0} - {}^3S_1 \qquad \Delta\nu_D = 2.76\times10^8\sqrt{T} \quad \text{sec}^{-1}$$

$${}^1P_1 - {}^1S_0 \qquad \Delta\nu_D = 2.14\times10^8\sqrt{T} \quad \text{sec}^{-1}$$

Therefore α is given by the square root of the ratio of the emitting gas temperature to the absorbing gas temperature T. In appendix C it is shown that for currents of about 1.5 ma through the light source, its temperature is about 320°K. 1.5 ma is the current used through most of the experiment.

$$\therefore \quad \alpha = \sqrt{\frac{320}{T}}$$

For absorption of less than about 40%, non-linear absor absorption effects can be ignored (reference 1 or 5), and the absorption is given by:

$$A_0 = \frac{k_0 L}{\sqrt{1+\alpha^2}} = \frac{\sqrt{T}\ k_0 L}{\sqrt{T+320}}$$

The expression relating k_o^o to the metastable density is[1]:

$$k_0 = \frac{2}{\Delta\nu_D}\sqrt{\frac{\ln 2}{\pi}}\ \frac{\lambda^2}{8\pi}\ \frac{g_2}{g_1}\ \frac{N}{T}$$

where λ is the wavelength of the radiation, g_1 and g_2 are the statistical weights of the normal and excited states respectively, and τ is the lifetime of the excited state (appendix A). The statistical weights are given by 2J + 1 with J a quantum number of the state[10]. Therefore, considering the lines of the multiplet separately, we have the results:

$$^3P_2 - {}^3S_1 \qquad K_{o_2} = \frac{2}{2.76\times10^{8}\sqrt{T}}\sqrt{\frac{\ln 2}{\pi}}\,\frac{(3889\times10^{-8})^2}{8\pi}\,\frac{5}{3}\,\frac{N}{2.81\times10^{-7}} = \frac{1.22\times10^{-12}N}{\sqrt{T}}$$

$$^3P_1 - {}^3S_1 \qquad k_{o_1} = \frac{2}{2.76\times10^{8}\sqrt{T}}\sqrt{\frac{\ln 2}{\pi}}\,\frac{(3889\times10^{-8})^2}{8\pi}\,\frac{3}{3}\,\frac{N}{2.82\times10^{-7}} = \frac{.730\times10^{-12}N}{\sqrt{T}}$$

$$^3P_0 - {}^3S_1 \qquad k_{o_0} = \frac{2}{2.76\times10^{8}\sqrt{T}}\sqrt{\frac{\ln 2}{\pi}}\,\frac{(3889\times10^{-8})^2}{8\pi}\,\frac{1}{3}\,\frac{N}{2.92\times10^{-7}} = \frac{.235\times10^{-12}N}{\sqrt{T}}$$

$$^1P_1 - {}^1S_0 \qquad k_{o} = \frac{2}{2.14\times10^{8}\sqrt{T}}\sqrt{\frac{\ln 2}{\pi}}\,\frac{(5016\times10^{-8})^2}{8\pi}\,\frac{3}{1}\,\frac{N}{2.20\times10^{-7}} = \frac{5.89\times10^{-12}N}{\sqrt{T}}$$

Our experiment does not distinguish between the three lines of the multiplet transition, so we have:

$$^3P_{2,1,0} - {}^3S_1 \qquad k_o = k_{o_2} + k_{o_1} + k_{o_0} = 2.18\times10^{-12}\frac{N_t}{\sqrt{T}} \quad \text{for triplets}$$

$$^1P_1 - {}^1S_0 \qquad k_o = 5.89\times10^{-12}\frac{N_s}{\sqrt{T}} \quad \text{for singlets}$$

Thus a measurement of absorption as a function of time in the afterglow reveals the time dependence of the metastable density. From this information the destruction coefficients may be determined.

The expression above for the triplets has really been slightly oversimplified. The absorption coefficient for the multiplet is the simple sum of absorption coefficients of the individual lines only in the approximation that the Doppler broadened lines overlap exactly and the probability for exciting all of the transitions are equal. At very low temperatures the lines don't overlap much, and an average of the three absorption coefficients weighted by the line strengths should be used. Then we would have the result (line strengths from appendix A):

$$K_o = \frac{.52\,k_{o_2} + .31\,k_{o_1} + .10\,k_{o_0}}{.52 + .31 + .10} = 1.05 \times 10^{-12} \frac{N_t}{\sqrt{T}}$$

The simple sum approximation has been used for all of our data analysis. The room temperature ratio of triplet to singlet density given by Benton, Ferguson, Matsen, and Robertson[12] for one per cent absorption is:

$$\frac{N_t}{N_s} = \frac{4 \times 10^9}{1.4 \times 10^9} = 2.86$$

We have :

$$\frac{N_t}{N_s} = \frac{k_o\sqrt{T}\,(2.18\times10^{-12})^{-1}}{k_o\sqrt{T}\,(5.89\times10^{-12})^{-1}} = 2.70$$

Therefore, the approximation isn't bad.

Apparatus

The central part of our apparatus is sketched in figure 1.

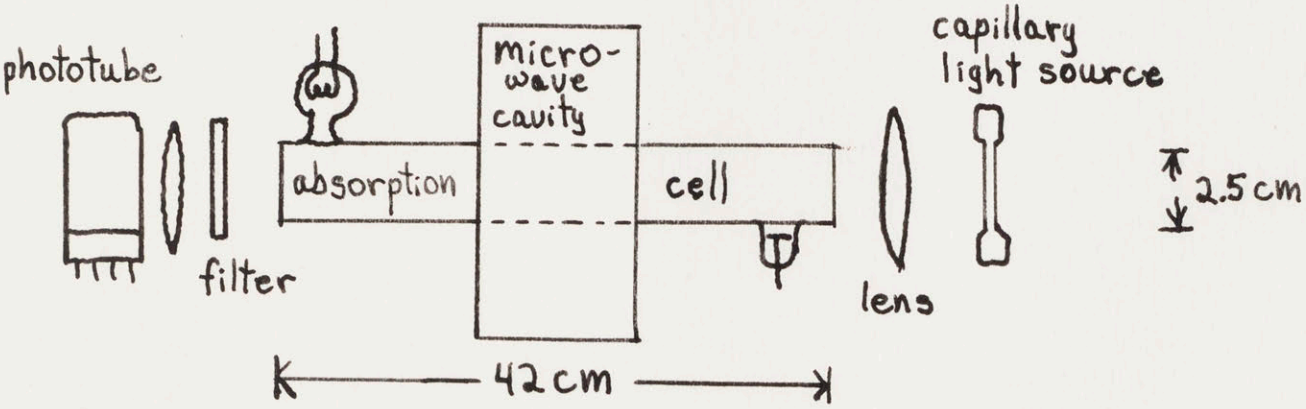


Figure 1. Apparatus

The interference filter passes a band of light of only a few angstroms width to insure that only one transition is being observed (appendix B). The microwave cavity was used for measuring the electron density[5]. The absorption cell and microwave cavity were wrapped with heating tapes to obtain the high temperature measurements and immersed in liquid nitrogen for low temperature measurements.

In figure 2 are two plots of absorption versus time for two different values of light source current. Since the time constant for a source current of seven milliamperes is seen to be only slightly less than the time

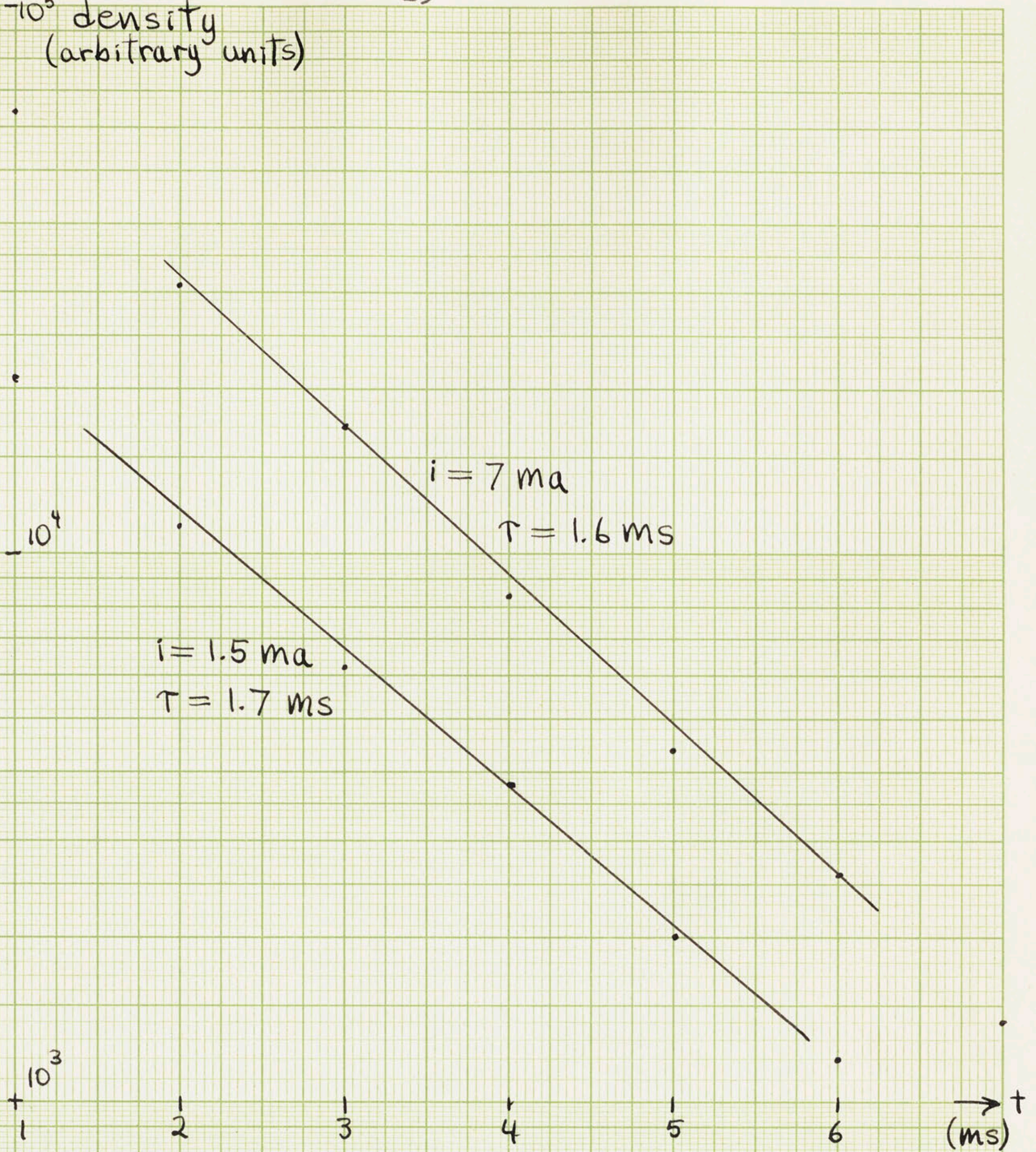


Figure 2 Depumping by Light Beam

constant for a current of one milliampere, depumping of the metastable state by the light beam has been assumed negligible.

The greatest problems encountered were with the vacuum system. These ranged from simple leaks to outgassing of the absorption cell cathode and trouble with the ion gauge. The whole system, including the liquid nitrogen trap, was baked at 500°K for a few days. Then the cathode was activated. A few times it was found that heating the cathode generated enough impurities that the baking had to be repeated. The ultimate pressure reached before helium was admitted and an experiment conducted ranged from $.8 \times 10^{-8}$ mm to about 4×10^{-8} mm. Our McLeod gauge was only accurate to a few percent, which introduced small errors in the diffusion measurements.

Our amplification and detection networks are very similar to the scheme developed by Phelps and Pack[3] and won't be detailed here. Essentially they involve a time sampling network to minimize noise and a gated photomultiplier. A special clipper powered by the discharge current was introduced to cancel the signal which leaked through the imperfectly gated photomultiplier during the discharge. Sixty cycle noise from the A.C. powered cathode was reduced by using a potentiometer to apply the high voltage symmetrically to both ends of the filament. Frequency beating of the time pulse generators with the A.C. line was eliminated by locking the generators to the line. A variable aperture was inserted between the absorption cell and the photomultiplier to check for non-linearity of the amplifiers, but none was detected.

The primary limitation on all of our measurements late in the afterglow was noise. Use of very stable power supplies eliminated all sources of noise except the random noise inherent in the photomultiplier tube itself. This was reduced somewhat by cooling the tube with dry ice, but the advantage proved to be not worth the inconvenience. Presumably the measurements could be greatly extended by using a liquid nitrogen immersed phototube.

^{3}S Metastable - Metastable Interaction

The ideal way to study the destruction of triplets resulting from metastable - metastable collisions would be to adjust the experimental parameters until destruction due to all other mechanisms is negligible. Then the metastable density is governed by the equation:

$$\frac{\partial N_t}{\partial t} = -2C\, N_t^2$$ with the solution:

$$\frac{1}{N_t} = 2Ct + \frac{1}{N_{t_0}}$$

Thus a plot of $1/N_t$ versus t should yield a straight line from which the constant C can be determined.

Diffusion losses are inversely proportional to pressure, and volume losses are proportional to the pressure squared. Therefore, to minimize the sum of these two loss terms, an intermediate pressure is necessary. Experimentally the minimum loss is found to occur for pressures of about five to ten millimeters of mercury. Since metastable - metastable destruction varies as $N_t{}^2$, it is desirable to maximize the metastable density. Metastable density is increased over a limited range by increasing the discharge current amplitude and duration. Unfortunately, an excessive current pulse results in emission during the afterglow which reduces the apparent absorption; so again a compromise is necessary. Another problem encountered was the fact that impurities were often present in the gas. The metastable states of the atoms may be destroyed by collision with the impurity particles. This process tends to further mask the metastable - metastable reaction. The net result is that the above simple relation is unusable.

Therefore, our original equation must be used. It can be written in the form:

$$\frac{\partial N_t}{\partial t} = -2CN_t^2 - kN_t$$

where the term kN_t represents the total of losses due to diffusion, collisions with neutral atoms, and collisions with impurity atoms. For the moderate discharges generally used when studying triplets, the singlets are destroyed very rapidly by collisions with electrons. Their effect on the triplet metastable density can be ignored a few hundred microseconds after the discharge. A typical log plot of experimental results versus time is shown in figure 3 with the regions of interest labeled. The metastable - metastable destruction can be recognized by a region of positive curvature with increasing time early in the afterglow. The term representing the formation of

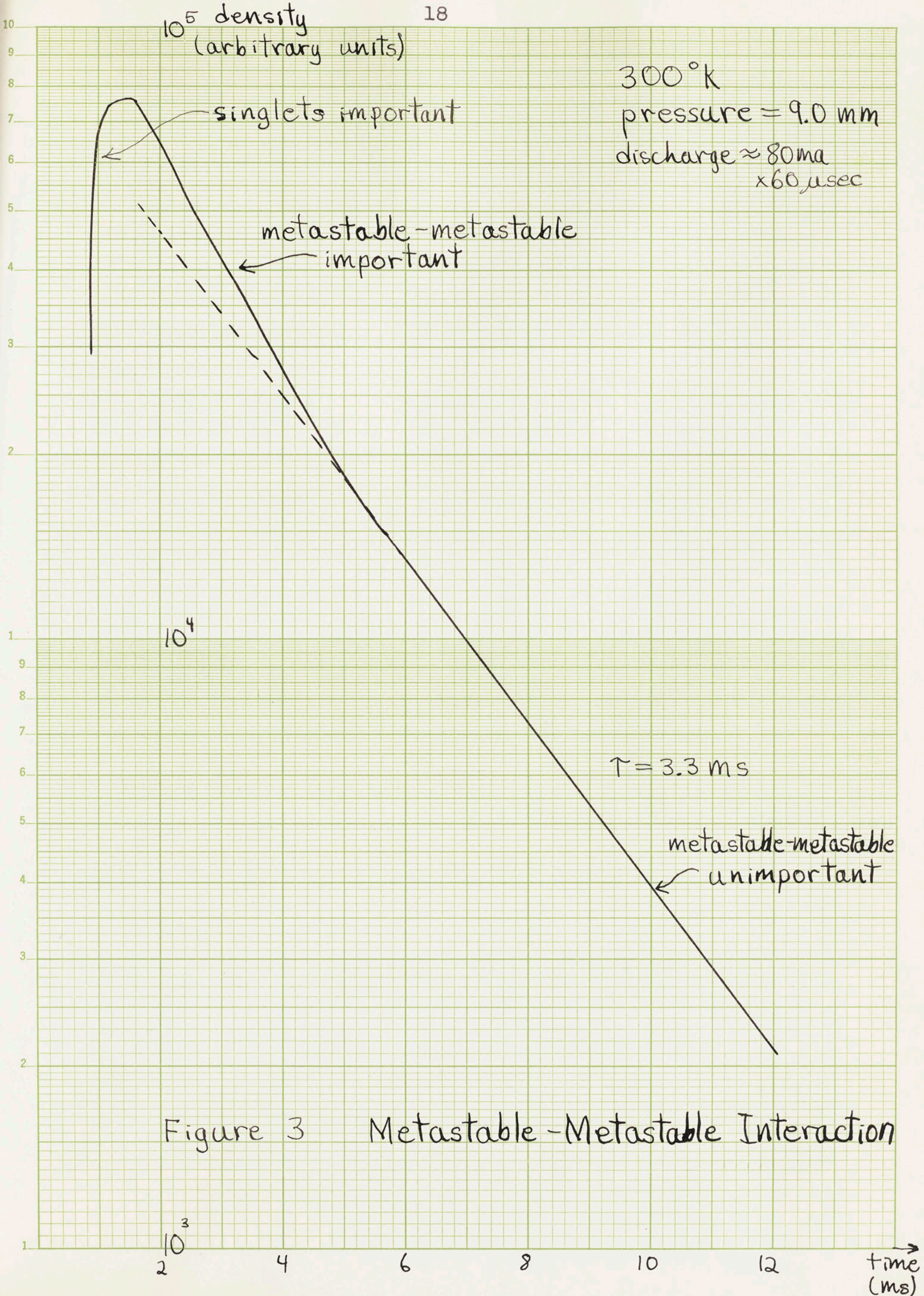


Figure 3 Metastable-Metastable Interaction

triplets from singlets can be recognized by a region of negative curvature early in the afterglow.

The time constant τ can be determined late in the afterglow, and then k is given by $k = 1/\tau$. A plot of $-\left(\frac{\partial N_t}{\partial t} + k N_t\right)$ versus N_t^2 yields the constant C. Such a plot is given in figure 4 in arbitrary units. The error brackets on the points on that graph result from the difficulty in determining precisely $\frac{\partial N_t}{\partial t}$ from a plot of N_t versus t on linear paper. The data points and error brackets imply a slope of about $2.26 \times 10^{-3} \pm .2 \times 10^{-3}$ still in uncalibrated units.

Calibration is accomplished by observing that the density in arbitrary units implied by the apparatus is 75,000 when the actual absorption determined from an oscilloscope is .429. We have from before:

$$\text{absorption} = A_0 = \frac{2.18 \times 10^{-12}}{\sqrt{T + 320}} L N_t$$

Therefore, N_t in cgs units is related to the N_t in our arbitrary units by:

$$N_t\,(\text{arb.}) = \frac{75{,}000}{.429} \; \frac{2.18 \times 10^{-12}}{\sqrt{T + 320}} L N_t\,(\text{cgs})$$

For $T = 300^\circ$K and the length of the absorption cell $L = 42$ cm, this becomes:

$$N_t\ (\text{arb.}) = 6.43 \times 10^{-7}\ N_t\ (\text{cgs})$$

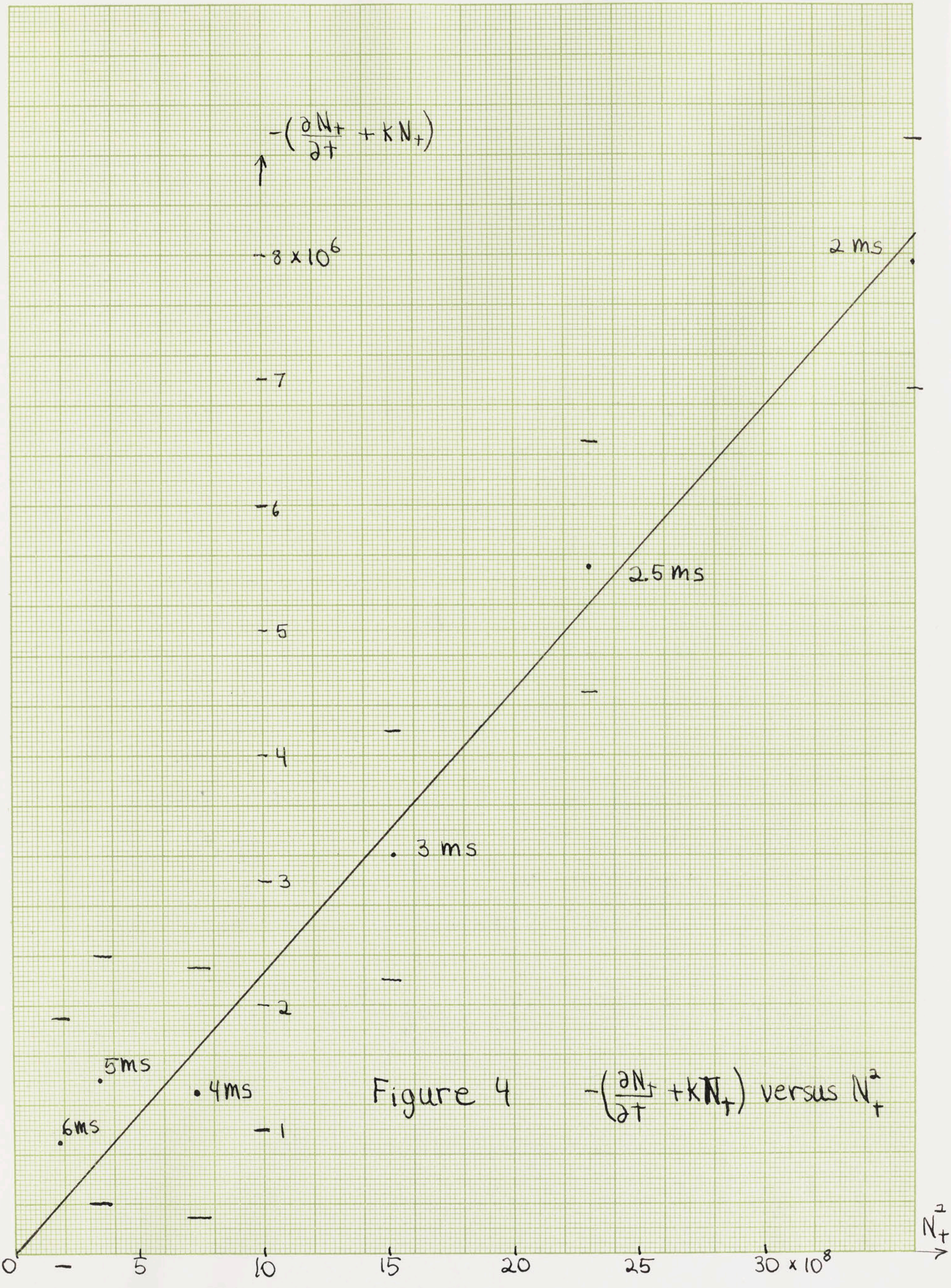


Figure 4 $-\left(\frac{\partial N_+}{\partial t} + kN_+\right)$ versus N_+^2

Therefore the slope previously determined becomes in cgs units:

$$\text{slope} = 2C = (2.26 \times 10^{-3} \pm .2 \times 10^{-3})(6.43 \times 10^{-7})$$

$$\therefore \quad C = 7.27 \times 10^{-10} \pm .6 \times 10^{-10} \left(\frac{cc}{atom}\right)\left(\frac{1}{sec}\right)$$

The results of similar data and similar calculations for the discharge operating at other temperatures are presented in figure 5 with a graph of C versus T.

An approximate value for the collision cross section can be obtained by assuming that each metastable has 3kT/2 of translational energy or:

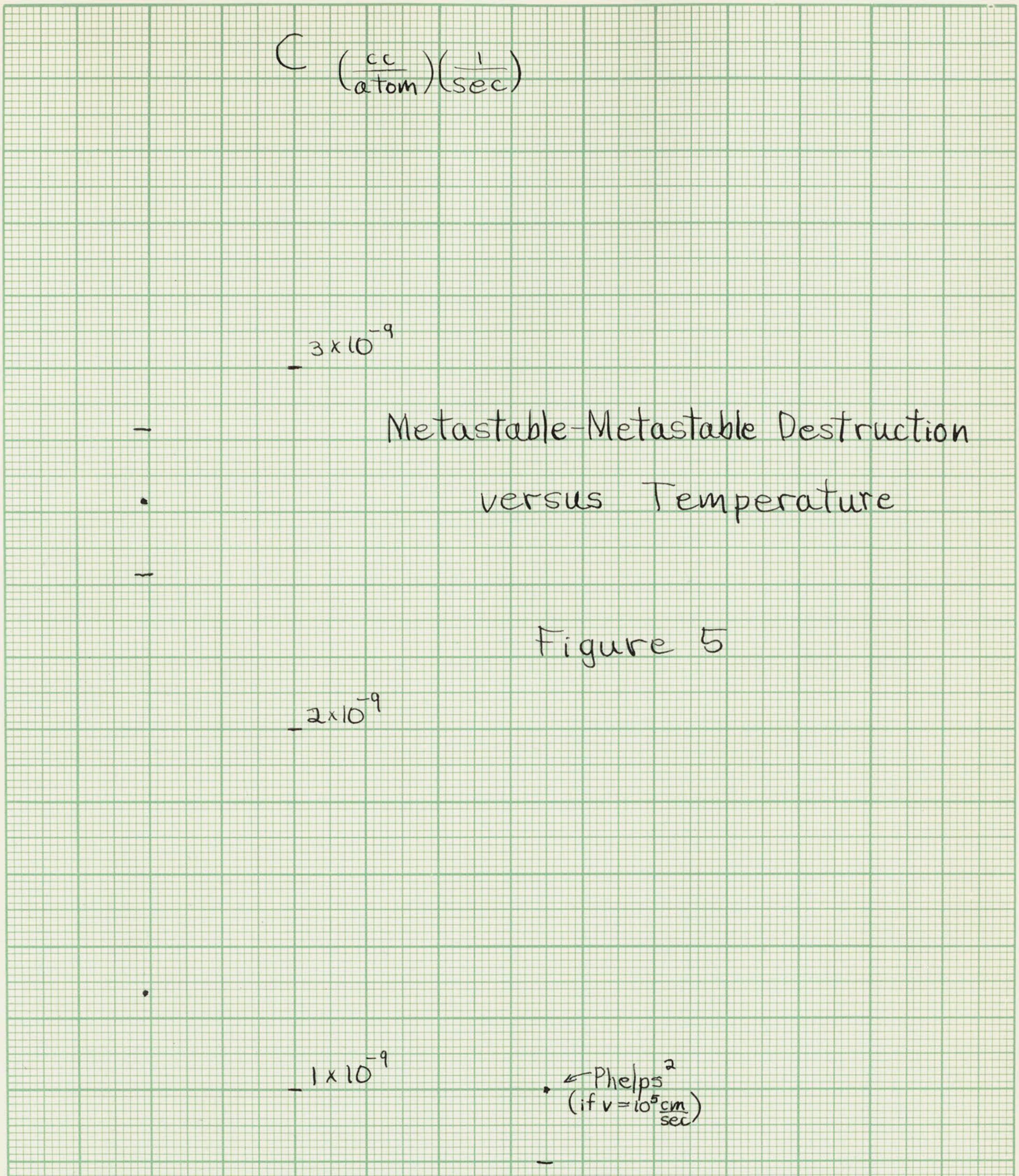
$$v = \sqrt{\frac{3kT}{m}} = \sqrt{\frac{3 \times 1.38 \times 10^{-16} \times 300}{6.68 \times 10^{-24}}} = 1.36 \times 10^{5} \ \frac{cm}{sec}$$

$$\text{cross section} = \sigma = \frac{C}{v} = 5.35 \times 10^{-15} \ cm^{2}$$

If we assume that the Doppler broadened lines of the triplet don't overlap at low temperatures we obtain instead of the value shown in figure 5:

$$C\Big|_{77^\circ} = 2.63 \times 10^{-9} \times \frac{1.05 \times 10^{-12}}{2.18 \times 10^{-12}} = 1.27 \times 10^{-9} \frac{cc}{atom\ sec}$$

We see that C doesn't vary strongly over a wide temperature range.



Metastable-Metastable Destruction versus Temperature

Figure 5

^{3}S Diffusion Coefficient

The equation governing the triplet density N_t is as discussed before:

$$\frac{\partial N_t}{\partial t} = D_t \nabla^2 N_t - B N_n^2 N_t + \beta n N_s - 2 C N_t^2 - \text{impurities}\, N_t$$

The easiest way to study the diffusion coefficient D_t is to adjust the experiment until the other destruction mechanisms are negligible. The metastable - metastable destruction is reduced by decreasing the discharge current amplitude and duration. The destruction by neutral atoms may be shown to be negligible by using experimental values for B determined by Phelps[4].

The possible destruction term due to collisions of metastables with impurity atoms is not so simple to eliminate from the above expression. Phelps and Molnar[2] made quantitative studies of the effects of various impurities at 300°K, and were able to eliminate them from their measurements of diffusion and volume destruction. In figure 6 is an experimentally obtained plot of destruction frequency versus pressure at 300°K using a gas sample which was several hours old and presumable dirty. It is compared to a similar plot obtained using the values determined by Phelps[4]. From this comparison it appears that the

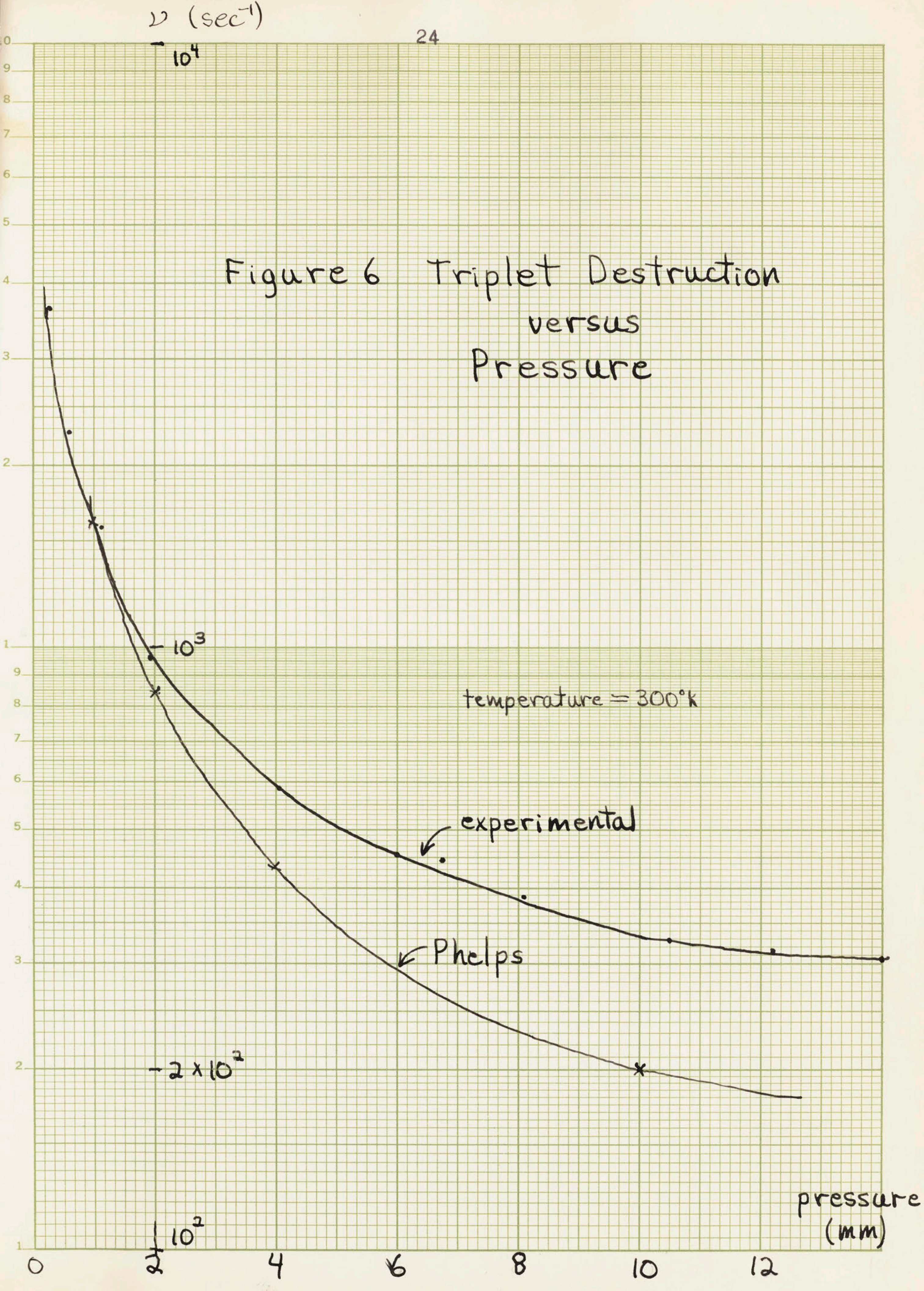


Figure 6 Triplet Destruction versus Pressure

impurities which we encountered are only important at pressures above two millimeters of mercury. I have assumed that this is true for all of my calculations. It would have been better to make a detailed study of the impurity effects at the temperatures used, but there was not sufficient time to do so.

An example of a diffusion measurement is shown in figure 7 with the metastable density plotted in arbitrary units. The metastable - metastable destruction term does not appear, and the singlet - triplet conversion is negligible after one millisecond. Therefore, we may use the equation:

$$\frac{\partial N_t}{\partial t} = D_t \nabla^2 N_t - B N_n^2 N_t$$ with the solution:

$$\nu_t = \frac{1}{\tau} = \frac{D_t}{\Lambda^2} + B N_n^2 \qquad \Lambda^2 = .25 \text{ cm}^2$$

From the graph τ = 1.04 msec.

From Phelps[4] $B = 2.5 \times 10^{-34} \dfrac{\text{cc}^2}{\text{atom}^2 \text{ sec}}$.

At 300°K and 1.9 mm mercury there are

$$\left(\frac{6.023 \times 10^{23}}{22.41 \times 10^3}\right)\left(\frac{1.9}{760}\right) = 6.71 \times 10^{16} \ \frac{\text{atoms}}{\text{cc}}$$

$$\therefore \nu_t = \frac{1}{1.04 \times 10^{-3}} = \frac{D_t}{.25} + 2.5 \times 10^{-34}(6.71 \times 10^{16})^2$$

$$D_t = 1.61 \times 10^{19} \pm .1 \times 10^{19} \left(\frac{\text{cm}^2}{\text{sec}}\right)\left(\frac{\text{atoms}}{\text{cc}}\right)$$

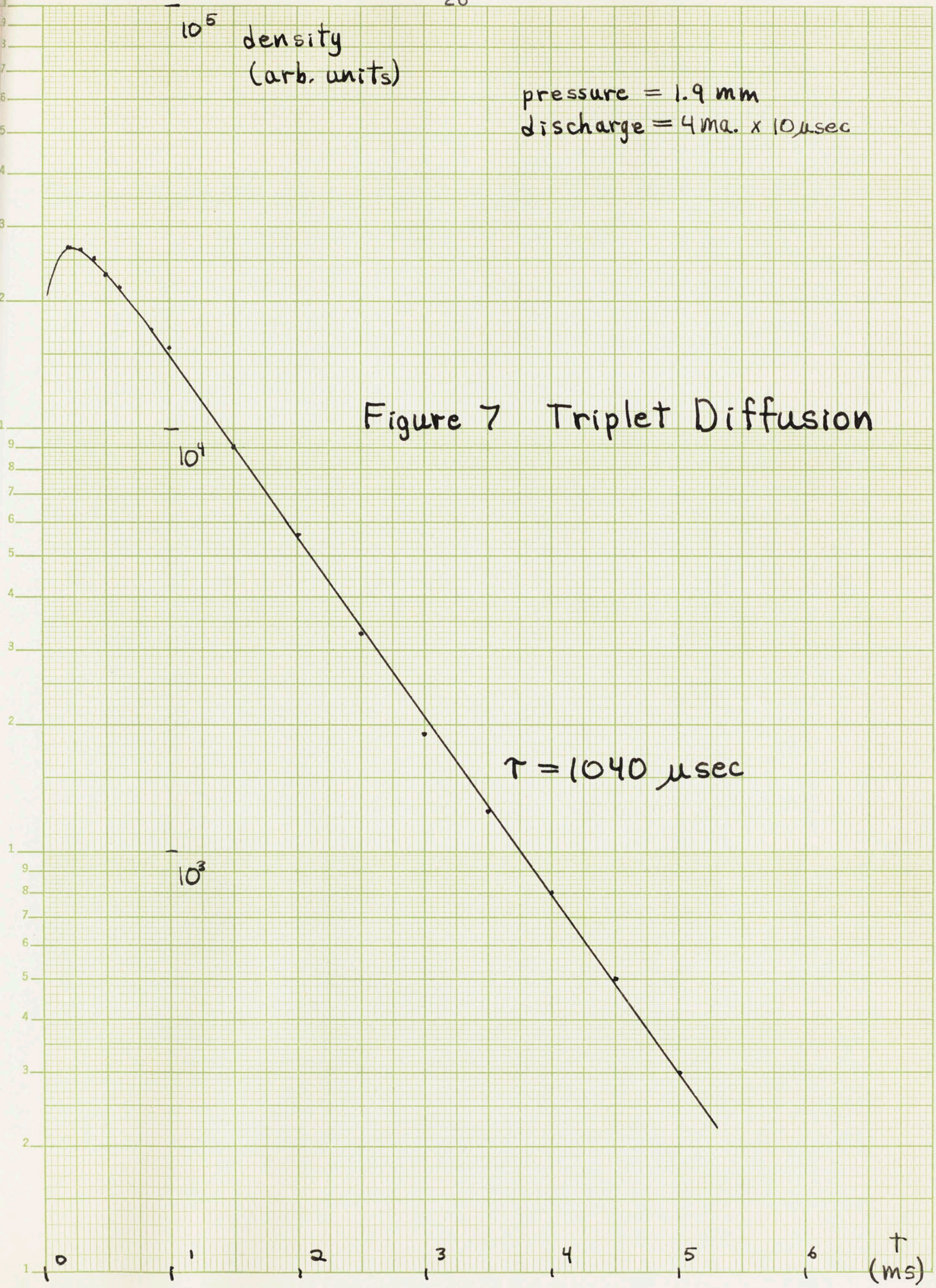
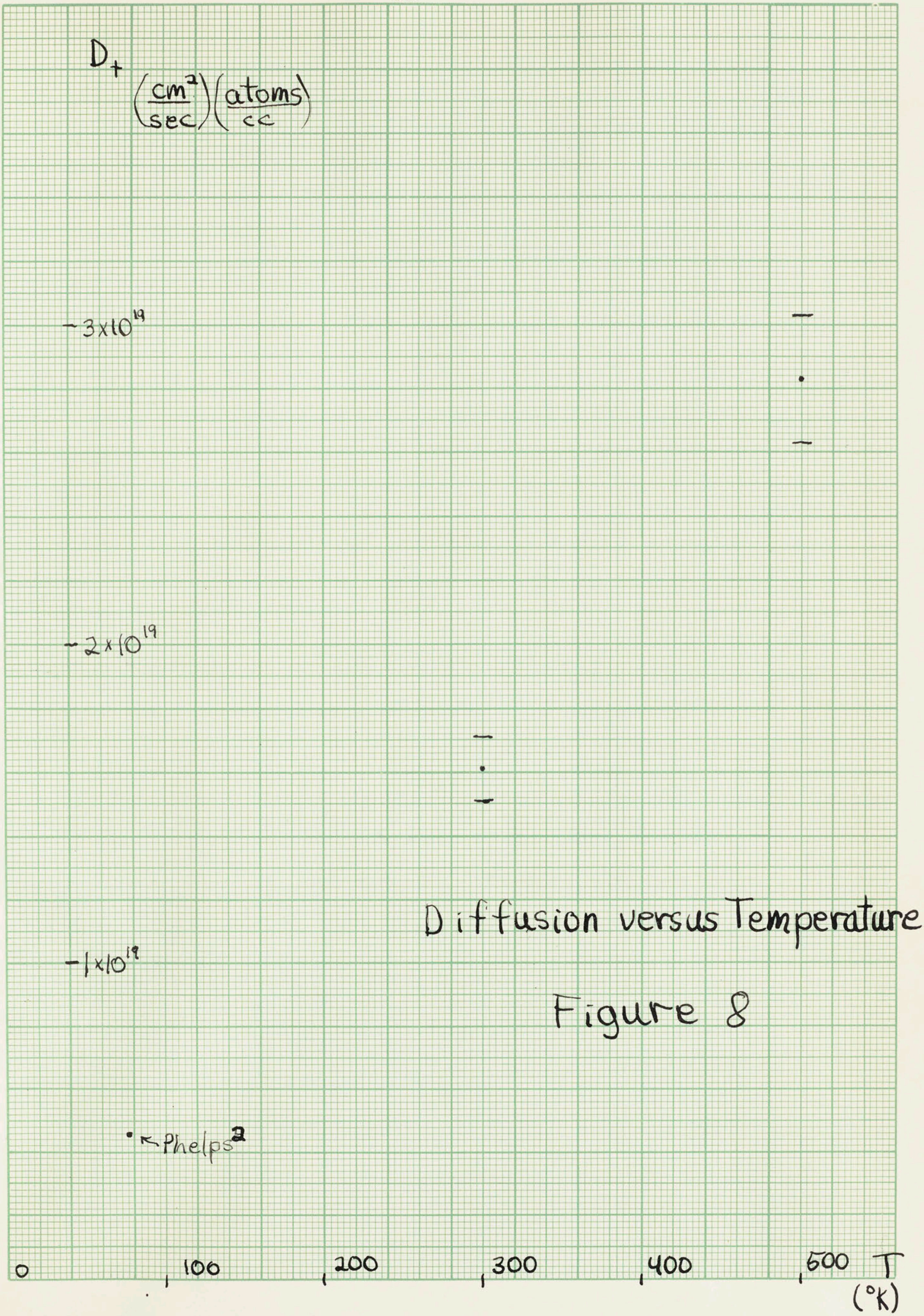


Figure 7 Triplet Diffusion

The error bracket on D_t is due to estimated possible errors in the McLeod gauge pressure measurements. Similar measurements were made at other temperatures, and the results are presented in figure 8. The diffusion coefficient for constant density is seen to be roughly proportional to the temperature. We have, according to Brown[13],

$$D = \left(\frac{V^2}{3\nu}\right)_{av} \qquad \text{where } V^2 = \frac{3KT}{m}$$

Therefore, we have the result that the collision frequency for constant density is nearly independent of temperature.



Diffusion versus Temperature

Figure 8

Conclusion

Unfortunately time was not available to really optimize the results. More extensive and precise values could have been obtained for the metastable destruction processes as functions of temperature. The apparatus began performing reasonable well only a few weeks before this experiment was to be finished.

Donald DeAngelis, another thesis student, has been partly responsible for the development and maintenance of the apparatus. His experiment dealt primarily with the singlet metastable state of helium, and his results include values for the destruction of singlets by superelastic collisions with electrons and the diffusion coefficient for singlets.

The author is grateful to Professor J. C. Ingraham for advice and encouragement during this project. Mr. J. J. McCarthy and Mr. William Mulligan provided generous technical assistance. Parts of the apparatus were constructed by John D. Litke, a thesis student last year.

Appendix A   Lifetime for Emission

The state ~~ls~~ $3p\,^3P_{2,1,0}$ is a closely spaced multiplet, and hence there are really three lines involved in emission of the 3889Å band. The transition probability for a particular line is given by Bates & Damgaard[6]:

$$P = \frac{64\pi^4}{3h}\frac{1}{g_2\lambda^3}S \quad \text{sec}^{-1}$$

where h is Plank's constant, λ is the wavelength of the line, g_2 is the statistical weight of the upper level of the line, and S is the line strength. This simplifies to :

$$P = \frac{2.02\times10^{18}}{g_2\lambda^3}S \quad \text{sec}^{-1}$$

where λ is in angstrom units and S is in atomic units. Line strength is given by $S = ML\sigma^2$ where M is a factor depending on the particular multiplet, L is a factor depending on the line of the multiplet and:

$$\sigma^2 = \frac{1}{(4\ell^2-1)}\left(\int_0^\infty R_i R_f\, r\,dr\right)^2$$

ℓ is the larger of the two azimuthal quantum numbers involved in the transition. R_i/r and R_f/r are respectively the initial and final radial wave functions of the active electron normalized in atomic units. Values of M are found using references 7 and 8. Values of L are found in reference 9, and σ^2 is tabulated for helium by Bates & Damgaard. The values of S for the states of interest are:

$^3P_2$ $\quad S = ML\sigma^2 = 3 \times \frac{100}{180} \times .31 = .52$

$^3P_1$ $\quad 3 \times \frac{60}{180} \times .31 = .31$

$^3P_0$ $\quad 3 \times \frac{20}{180} \times .31 = .10$

$^1P_1$ $\quad 1 \times 1 \times .87 = .87$

The statistical weights of the states are[10]:

$^3P_2$ $\quad g_2 = 2J + 1 = 5$

$^3P_1$ $\quad 3$

$^3P_0$ $\quad 1$

$^1P_1$ $\quad 3$

Hence, the transition probabilities are:

$^3P_2 - {}^3S_1$ $\quad P = \frac{2.02 \times 10^{18} S}{g_2 \lambda^3} = \frac{2.02 \times 10^{18} (.52)}{5\,(3889)^3} = 3.56 \times 10^6 \text{ sec}^{-1}$

$^3P_1 - {}^3S_1$ $\quad \frac{2.02 \times 10^{18} (.31)}{3\,(3889)^3} = 3.54 \times 10^6$

$^3P_0 - {}^3S_1$ $\quad \frac{2.02 \times 10^{18} (.10)}{1 \times (3889)^3} = 3.42 \times 10^6$

$^1P_1 - {}^1S_0$ $\quad \frac{2.02 \times 10^{18} (.87)}{3\,(5016)^3} = 4.54 \times 10^6$

The lifetimes are[1]:

$^3P_2 - {}^3S_1$ $\quad \therefore\ \tau = \frac{1}{p} = \frac{1}{3.56\times10^6} = 2.81\times10^{-7}$ sec

$^3P_1 - {}^3S_1$ $\quad \frac{1}{3.54\times10^6} = 2.82\times10^{-7}$ sec

$^3P_0 - {}^3S_1$ $\quad \frac{1}{3.42\times10^6} = 2.92\times10^{-7}$ sec

$^1P_1 - {}^1S_0$ $\quad \frac{1}{4.54\times10^6} = 2.20\times10^{-7}$ sec

Appendix B Line Broadening

The energy levels of the states which we are concerned with are[11]:

$^3S_1$	$k = 159850.318 \ \mathrm{cm}^{-1}$
$^1S_0$	166271.70
$^3P_2$	185558.92
$^3P_1$	185559.085
$^3P_0$	185559.277
$^1P_1$	186203.62

The maximum separation of the components of the triplet band is: $\Delta\nu = c\,\Delta k = 3\times10^{10}(.36) = 1.1\times10^{10}\ \mathrm{sec}^{-1}$

The Doppler broadening is[1]:

$$\Delta\nu_D = \frac{2\sqrt{2R\ln 2}}{c}\,\nu_0\sqrt{\frac{T}{M}}$$

where R is the gas constant, ν_0 is the frequency of the radiation, T is the gas temperature, and M is the molecular weight.

$$\therefore\ \Delta\nu_D = \frac{2\sqrt{2\times8.31\times10^7\times.693}}{3\times10^{10}}\,\nu_0\sqrt{\frac{T}{M}}$$

$$= 7.16\times10^{-7}\,\nu_0\sqrt{\frac{T}{M}}$$

For helium $\Delta \nu_D = \frac{7.16 \times 10^{-7}}{\sqrt{4}} \nu_0 \sqrt{T} = 3.58 \times 10^{-7} \nu_0 \sqrt{T}$ sec^{-1}

$^3P_{2,1,0} - {}^3S_1$ $\Delta \nu_D = 3.58 \times 10^{-7} (3 \times 10^{10})(2.57 \times 10^{4}) \sqrt{T} = 2.78 \times 10^{8} \sqrt{T}$

$^1P_1 - {}^1S_0$ $\Delta \nu_D = 3.58 \times 10^{-7} (3 \times 10^{10})(1.99 \times 10^{4}) \sqrt{T} = 2.14 \times 10^{8} \sqrt{T}$

Natural broadening also occurs because of the finite lifetime (appendix A) of the state[1].

$^3P_{2,1,0} - {}^3S_1$ $\Delta \nu_n = \frac{1}{2\pi\tau} = \frac{1}{2\pi(2.8 \times 10^{-7})} = 5.68 \times 10^{5}$ sec^{-1}

$^1P_1 - {}^1S_0$ $\frac{1}{2\pi(2.2 \times 10^{-7})} = 7.24 \times 10^{5}$ sec^{-1}

Thus natural broadening is negligible compared to Doppler broadening. Mitchell and Zemansky[1] found that for this type of absorption experiment Lorentz and other types of line broadening are unimportant in comparison to Doppler broadening and natural broadening, so calculations need not be carried out here.

The passband of the 3889Å interference filter was 25Å, and that of the 5016Å filter was 5Å.

$^3P_{2,1,0} - {}^3S_1$ $\Delta \nu_f = \frac{c}{\lambda^2} \Delta \lambda = \frac{(3 \times 10^{10})(25 \times 10^{-8})}{(3889 \times 10^{-8})^2} = 4.94 \times 10^{12}$ sec^{-1}

$^1P_1 - {}^1S_0$ $\frac{(3 \times 10^{10})(5 \times 10^{-8})}{(5016 \times 10^{-8})^2} = .595 \times 10^{12}$ sec^{-1}

Therefore, the filters pass completely the Doppler broadened lines.

Appendix C Temperature of Light Source

We have the formula for absorption (from introduction):

$$A_0 = \frac{k_0 L}{\sqrt{1+\alpha^2}} = \frac{k_0 L}{\sqrt{1+\frac{T_{source}}{T_{abs.}}}}$$

Late in the afterglow of the discharge the temperature of the absorbing gas is room temperature or 300°K. In figure 9 is a plot of absorption versus light source current for fixed discharge and time delay conditions. Absorption was determined from rough scope measurements. The data points imply a downward sloping curve, which is reasonable since the temperature of the emitting gas is expected to increase with current. By extrapolation the fractional absorption is found to be .255 when the source current is zero. But for zero source current the temperature of the light source must be 300°K.

$$\therefore \quad .255 = \frac{k_0 L}{\sqrt{1+\frac{300}{300}}} \qquad k_0 L = .360$$

Then the temperature of the source can be determined for a current of 1.5 ma (the value usually used in data taking).

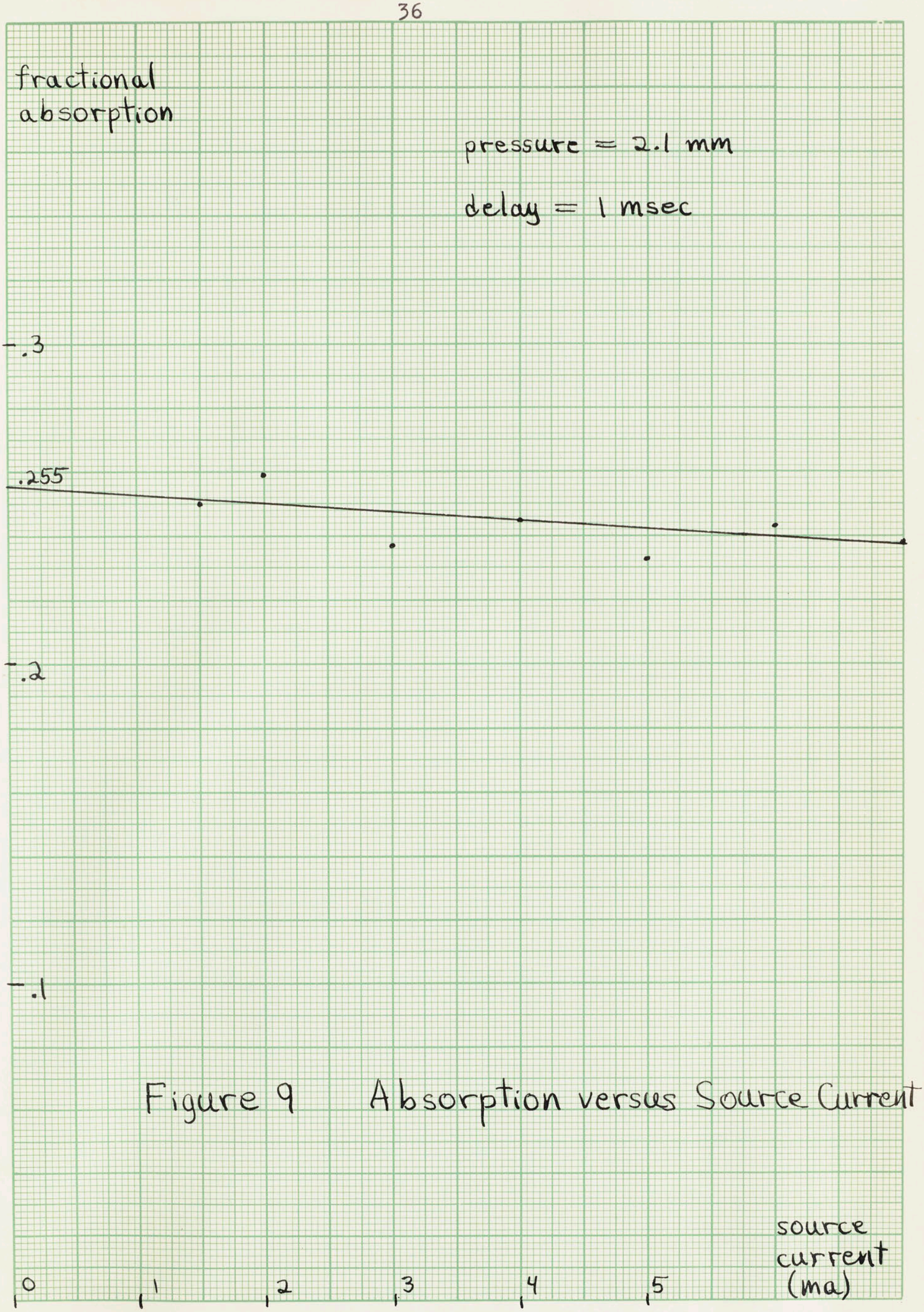


Figure 9 Absorption versus Source Current

$$.250 = \frac{.360}{\sqrt{1 + \frac{T_{source}}{300}}} \qquad \therefore\ T_{source} \approx 320^{\circ}K$$

This method of temperature measurement is capable of greater accuracy than is implied by the rather poor data of figure 9. Since the measurement is made by a sampling technique, it could readily be applied to a pulsed light source.

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