MASTER

SCR-104

215

Sandia Corporation

... RESEARCH COLLOQUIUM

**SOME MICROWAVE STUDIES
OF GASEOUS PLASMAS**

by

L. Goldstein

July 1959

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

SANDIA CORPORATION RESEARCH COLLOQUIUM

A lecture delivered at
Sandia Corporation
Albuquerque, New Mexico
8 April 1959

Published under the auspices of the
Colloquium Committee
Craig C. Hudson, Chairman

The Sandia Corporation Research Colloquium provides an opportunity for free exchange of information and ideas on subjects of interest to the scientists and engineers of Sandia Corporation. The fact that speakers are invited to express their ideas freely does not imply indorsement of their views by the Corporation.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

Printed in USA. Price \$1.00. Available from the Office of
Technical Services, Department of Commerce,
Washington 25, D.C.

SCR-104
TID-4500 (14th Edition)
Physics and Mathematics

SANDIA CORPORATION
RESEARCH COLLOQUIUM

SOME MICROWAVE STUDIES OF GASEOUS PLASMAS

by

L. Goldstein
University of Illinois

July 1959

SOME MICROWAVE STUDIES OF GASEOUS PLASMAS

Since the subject of my talk, gaseous plasmas, is very broad, I want first to define the type and nature of the plasmas I will be concerned with. Later I hope to show that most of the significant results we have reached by studying certain plasmas are quite general and may indeed be applied to large classes of plasmas. In presenting the main points of the studies I have made, I want to emphasize the physical phenomena rather than to succumb to the ever present temptation of enveloping them in mathematics. To conclude this introduction, let me say that since the techniques used in plasma experiments may not be too familiar to non-specialists I shall do my best to describe at least briefly the principles on which they are based.

To establish a basis for our discussion, let us consider a mixture of perfect gases in a given volume. The total pressure in this volume will be the sum of the partial pressures of the constituents. That is,

$$P_t = P_0 + P_1 + P_2 + \dots$$

We can also say that,

$$P_t = N_{()} kT_{()},$$

where

N = the number density of the gases

T = the temperature of the gases

$()$ = appropriate indices

Let us imagine next that we have ionized the gas. We can consider the ionized gas as a mixture of these constituent gases: the gas of the neutral molecules, the gas of the ions (positive and negative), the gas of the electrons, and in some cases, the gas of the photons. We may then say that

$$P_t = N_0 k T_0 + N_1 k T_1 + N_2 k T_2 + N_3 k T_3 + \dots$$

Here the subscript 0 indicates the values for the neutral un-ionized gas -- whether it is in an excited state is immaterial for the time being. The subscripts 1, 2, and 3 may indicate, for instance, electrons, positive ions, and negative ions, respectively. In this discussion, we will neglect the photon gas as a plasma constituent, even though in some particular cases it may play a significant role. A glance at the formula makes it apparent that the relative and absolute values of the number densities and temperatures may vary in an almost infinite manner. Consequently, it is possible to have plasmas in a very great variety of states, and it is our obligation to define the states of the plasmas we wish to talk about.

However, before defining our plasmas, let us simplify further by assuming plasmas that contain no negative ions. That will leave only electrons, positive ions, and neutral molecules to be dealt with. This being so, we can define a number (δ) that is fairly characteristic of plasmas:

$$\delta = \frac{N_i}{N_m + N_i}$$

where N_m is the number density of the neutral molecules and N_i is the number density of the positive ions. Note that δ , which is really a measure of the degree of ionization of the plasma, is independent of the absolute values of these numbers. It may vary from 0 or no ionization to 1 or complete ionization. Now, it is possible to have either complete ionization or at least a very high degree of ionization in a plasma of extremely low density. The plasmas of interstellar space are a good example. The properties of low-density plasmas will, of course, be entirely different from those of high-density plasmas, despite the fact that their degrees of ionization are the same. Today I will discuss plasmas with a degree of ionization less than 10^{-3} . Incidentally, only recently have we been able to produce in the laboratory almost completely ionized plasmas; before, the degree of ionization seldom exceeded 10^{-3} .

Since, as we have seen, the temperatures of the gaseous constituents can vary tremendously, we will further limit our conditions by considering only plasmas with approximately equal constituent temperatures. In other words, in their initial and final states our plasmas will be essentially isothermal or nearly so at the temperature of a reservoir.¹ (If plasmas, once cut off from the source of energy that maintained them, are placed in a heat

¹J. M. Anderson and L. Goldstein, Phys. Rev., 100, 1037-1046 (1955).

reservoir, sooner or later the temperatures of the various constituents will reach the reservoir temperature). Non-isothermal plasmas, however, are in general, of greater interest, because the interaction processes that lead to a temperature equilibrium are the cause of all the phenomena, whether observable or unobservable, that take place in plasmas and that we wish to investigate. We will therefore deviate our plasma slightly from its initially isothermal state and will study the various ways by which it returns to this isothermal state.

Having defined the kind of plasmas we are going to be working with, we have next to find how to produce them. When a plasma is in one or more external electromagnetic fields, the fields can supply energy to all of the charged constituents or to either the electrons or ions selectively. (The fields do not, of course, supply energy to the neutral molecules directly). And if a plasma is in contact with a source that supplies energy either selectively to some constituents or to all the constituents, but at unequal rates, no temperature equilibrium can be reached. However, if energy is supplied to a plasma and then cut off, the various gases constituting the plasma will come into temperature equilibrium at the temperature of the reservoir.²

Is it not obvious now how we may produce and work with an isothermal plasma? Suppose that in a rare gas we produce a pulse discharge with a duration of about 2 microseconds. Actually the duration of the pulse and the consequent excitation of the plasma is of little importance; what is really important is cutting off the discharge. In Figure 1, the number densities of the charges (N_e for electrons, N_i for ions) are plotted against time. We see that after the plasma has been cut off from the energy source, the charge density decays. There are two processes at work in this decay -- recombination and diffusion. (Remember that we have said that there are no negative ions present. There is really still another way of producing decay in the electron density of a plasma. Under certain conditions, electrons may be captured by certain types of molecules and atoms, thereby producing negative ions. This process, naturally enough, decreases the number density of electrons and increases the number density of negative ions. By secondary processes these negative ions may combine with positive ions. However, in these experiments the plasmas are produced in the chemically inert noble gases, and therefore no negative ions are present. So today let us confine our attention to the two main processes mentioned above). We know that the electron temperature must be high in order to produce the plasma, production of a gaseous discharge plasma being an essentially thermal process. That is, electrons being in a distribution of velocities, those at the high-energy end of the distribution are responsible for producing new electrons by ionization. After the plasma-excitation energy pulse has been cut off (A in the figure), the electron temperature will drop to

²L. Goldstein, Advances in Electronics and Electron Physics, VII (1955), 473 (and references), (Academic Press, Inc., New York 10, New York, Editor: L. Marton).

the temperature of the gas that is in contact with the reservoir (see dotted curve in the figure). The duration and rate at which this is taking place depend upon the intensity of the discharge (N_e , N_i), the nature and pressure of the gas, and the geometry of the experiment. The temperature will then remain constant, and we will have an isothermal plasma while it lasts.

Since in this process the degree of ionization (and therefore the number density of the electrons) is decaying, we have the possibility of studying isothermal plasmas at various degrees of ionization. We have, however, first to find a way of exploring a plasma in such a manner that the electron density does not decay significantly while we are at work. Microwaves are a convenient tool for this purpose, for they can be propagated in such very narrow pulses that there is no noticeable decay in charge density during their propagation through the plasma.

Suppose that we produce a decaying plasma in one of the rare gases and that recombination is one of the determining processes of the decay. The recombination of electrons with positive ions will then produce a change in light intensity called afterglow. Light intensity ($L. I.$) is plotted versus time in Figure 2. You can see that during the initial excitation pulse, the light intensity is very great. Shortly thereafter it decays, rises once again, and then again decays. This is the characteristic shape of light output from a plasma. It is very easy, of course, to observe the light intensity in experiments by using photomultipliers or photocells.

Let us return to our isothermal plasma, in which, you will remember, the electron, ion, and neutral molecule temperatures were all equal to the reservoir temperature. Microwaves propagated in the plasma will interact selectively with the electrons and heat them. But if we raise the electron temperature, the plasma deviates from its isothermal state. (Incidentally, the temperatures of the ion and neutral molecules would still be equal, for they are in excellent thermal contact.) In case you are interested in the reason for this selective heating, let me say that it is caused by the fact that the energy transfer from the electron gas to the heavier constituent gases is not very efficient. In our experiments, we vary the isothermal temperature from 77°K to several hundred degrees K, so you can see that we are dealing with relatively cold plasmas.

Now we come to something interesting. When a microwave pulse is propagated in a plasma in such a manner that some of the pulse energy is absorbed by the electron gas, two effects follow. The electron temperature rises and the light intensity decays at the moment of energy absorption (see B in Figure 2). In other words, the recombination coefficient of the electrons with the positive ions is an inverse function of electron temperatures. This is perhaps understood more easily if it is pointed out that an electron-ion recombination is nothing more than a kind of electron-ion collision. But if the colliding particles have large relative velocities, their chance of combining is small. To return to the main point: The consequence

Figure 1 -- Number density of electrons and ions versus time;
electron temperature versus time

Figure 2 -- Light intensity versus time

of all this is that such a plasma can be used as a photodetector for microwaves. In fact, detecting microwaves by this "inverse photoeffect" is our main method of studying plasmas.

Thus far we have seen that the electron temperature can be raised by absorption of microwave energy. Suppose now that we introduce into the plasma a microwave pulse of such small amplitude that there is no detectable rise in electron temperature. It is clear then that we can propagate not one microwave but at least two independent waves in a plasma. One may be used to disturb the plasma and the other to sense and observe the disturbance. These waves can be propagated simultaneously or one in the wake of the other. This is a basic method in our experiments. The disturbing wave is designated by ω_d , and the wanted or sensing wave by ω_s or ω_w .

Figure 3 shows a typical, though early, experimental setup. The microwaves are propagated in the waveguide shown. The large dip in the waveguide enables us to plunge it into liquid nitrogen to produce low-temperature plasmas down to 77°K. Figure 4 is another view of an experimental layout. A few points here may be of interest. The plasma tube, of course is inside the waveguide. Crystals are used to detect the microwaves. The holes in the waveguide provide locations for photocells. Various locations are desirable, for if the microwaves are attenuated as a function of distance, the difference in the quenching of light intensity recorded by the photocells at various distances will show it.

Look now at the traces on Figure 5. To produce the plasma, we used short-duration DC pulses which could be reproduced at regular intervals. The figure shows the time interval between two discharges; that is, the time between one plasma being produced and then another. I would like to draw your attention first to the lower trace which is a crystal output of the detected continuous wave of 9400 megacycles per second at a very low amplitude. The transmission of this wave is modulated by the decaying plasma. I do not want to go very deeply at this time into the reasons for the fancy wiggles in the curve. Briefly, the shape of the transmitted wave is a result of the different types of collisions involved in the decay of the electron temperature. The upper trace is the output of a photomultiplier scanning the plasma from a fixed point. You can see how the light intensity varies with time and how it follows the decay in electron density, when, during the course of the decay, we introduce a disturbing wave pulse after equilibrium temperature has been reached. Whereas the low-level signal can be propagated at a microwatt level, the disturbing signal must be propagated at a milliwatt level. Now, the introduction of this disturbing signal causes the continuous wave to undergo a modulation during the presence of the disturbance, while at exactly the same time, the light intensity is quenched. In fact, the most important information furnished by the figure is that these two events are simultaneous. Perhaps I can put this whole thing in a different

Figure 3

Figure 4

Figure 5

form. When the plasma is disturbed, both the electron collision frequency and the transparency of the plasma to RF waves are altered at the same time. Hence we see that the electron collision frequency increases, and as a result, the transmitted signal of the continuous wave decreases, and the recombination light intensity also decreases.

Figure 6 illustrates the point that whenever a disturbing pulse is introduced into a plasma, a quenched light pulse also occurs. Here we have varied the time at which the pulsed waves were introduced. This is a record from an experiment made on neon at one millimeter of mercury pressure and at approximately room temperature. The quenched light pulse, you will notice, is very much wider here than on the previous slide. This merely means that the pulse decay time is longer than the disturbing pulse width. The reason is that at this pressure the thermal contact between the electrons and the neon gas is not good enough to allow the electrons to cool off with sufficient rapidity, and so it takes longer for the electrons to recover their original temperature and follow the recombination light intensity. [This latter is relative to the isothermal or original (room) temperature of the electrons].

Figure 6

Just what can we study in plasmas by means of these microwaves and photo-quenching effects? Well, the electrons interact with neutral molecules, with ions, and with each other. Since all observable phenomena result from these interactions, it follows that we can obtain generalized results for all plasmas in which interactions take place by establishing the laws of interaction between the electrons and the plasma constituents. In practice, our investigations center on the rare gases, principally because negative ions are not produced in these gases and we prefer, as I have had occasion to mention, not to work with negative ions. So we transmit a disturbing signal through a rare-gas plasma, and at the same time transmit a low-level, high-frequency microwave as a detector of the disturbance produced. Because the electron temperature can be deviated in a known way by using disturbing signals of the appropriate amplitude and frequency, we have a way of establishing the laws of the collision processes which occur between electrons and molecules in these gases.

Figure 7 shows the modulated traces of the transmitted sensing wave signals (2) through disturbed (1a) initially room-temperature plasmas established in the five rare gases -- xenon, krypton, argon, neon, and helium. The case of neon is, however, very peculiar, as we shall see later. In the figures, 1a shows the shape of the disturbing pulse in the absence of a plasma. You can also see the trace of the 9400 megacycle wanted wave which is transmitted through the plasma some time during the after-glow but in the absence of disturbance. If the disturbing wave and the sensing wave are propagated simultaneously, the sensing signal deforms immediately. Note the following: When we use a disturbing pulse to increase the electron temperature in the plasma, thereby varying the collision frequency of the electrons, the result is a curve of the collision frequency of the electrons with the atoms as a function of the electron temperature. This curve enables us to determine the corresponding collision cross sections. When we stop the disturbance and allow the electron gas to cool off, the same curve is retraced the other way around in time.

It is also of interest that not only the wanted signal but also the disturbing signal may be distorted under certain conditions (1b), namely, when the pulse width of the disturbing signal is broad enough to permit observation of what is left of the signal after its traversal of the plasma. What happens here is, in a way, that the leading edge of the disturbing signal makes a path for itself in the plasma, allowing part of the pulse to pass through with little disturbance, while the electron temperature is such that the collision frequency is minimum.

Now in the case of xenon, for example, because of moderate heating of the electron gas, the plasma becomes more transparent than it was when the electron gas was at room temperature. It follows from this observation that the cross section drops with the increased

Figure 7

electron energy; with more intense heating the collision frequency goes through a minimum, then increases when the electron energy is further increased. These experiments with rare gases are in a sense unique, because before they were made there was no way in which to show the over-all variation with electron temperature in the cross sections of the Ramsauer rare gases (xenon, krypton, and argon) for electrons at room temperature or lower. In the past, phenomena such as we are speaking of could be studied only with electron beams, and one simply cannot form electron beams of the order of a few hundredths or thousandths of an electron volt. In the experiment I have just described, on the other hand, the electron gas has at room temperature an equivalent mean energy of 0.04 electron volt.

The slide we are discussing shows similar pictures for krypton and argon. Note that with these gases the collision cross sections for electrons also go through a certain minimum as a function of electron temperature. Again, this means that when the electron energy has reached a certain value -- it is about 0.3 to 0.4 electron volt -- these gases become essentially transparent to electrons of this energy range. Or, to phrase it differently, the collision frequency of the electrons in these gases is decreasing significantly in that energy region. Look now at the picture in helium. You see two different signals for two different amplitudes of the disturbances, but there is no Ramsauer effect. When we made these experiments several years ago, we expected no Ramsauer effect in neon either. And in truth there was none, although it looks as if there were. To discover the reason for this apparent effect, we investigated neon further and were able to show that the observed effect was due to the collision of electrons with neon ions, in addition to collisions with neon atoms. In any low temperature plasma, even those with a low degree of ionization, there are electron-ion collisions that may become significant enough to overwhelm the electron-molecule effects. In neon gas this is the case at temperatures of 300°K or lower, in spite of the fact that the degree of ionization is only on the order of 10^{-5} . This finding induced us to investigate electron-ion collisions more closely, a subject to which I shall return later.

However, to show that the effect in neon was not a Ramsauer effect, we had merely to increase the number density of the molecules enough to eliminate any possible ion effects (Figure 8). Here the neon is at a pressure of 20 millimeters of mercury. The number density of the charges is essentially the same as in the previous neon example, but in view of the high pressure the degree of ionization has decreased. The result is that the chances of any effect other than electron-molecule collisions has been decreased. You see that when we vary the amplitude of the disturbing pulse (1), we vary also the amplitude of the wanted signal transmitted through the plasma (2a, 2b, . . . 2i). You will note particularly that there is no sign of a Ramsauer effect. All these experimental results can be calculated. The figure, in fact, shows both the calculated and observed values; there is no mystery about the matter.

CROSS-MODULATION OF E.M. WAVES IN A DECAYING
GASEOUS DISCHARGE PLASMA NEON 20 mm. Hg.

ELECTRON COLLISION FREQUENCY, $\nu(t)$
FOR ARBITRARY DISTURBING WAVE POWERS

$$\nu' = \left[\nu_0^2 + \left(\frac{e^2}{n^2 L^2 G \omega_0^2} \right) E_0^2 \right]^{1/2}$$

SIMILARITY OF COMPUTED ELECTRON COLLISION FREQUENCY TO CROSS-MODULATION FROM EXPERIMENT

Figure 8

Perhaps at this point, it would be wise to tell you more exactly what microwaves do in the plasma. High-frequency electromagnetic waves interact only with electrons because only electrons are light enough to oscillate at the frequency of the waves. In a vacuum, electrons oscillate with their velocity out of phase with the microwave field. In a gaseous plasma, however, the electrons collide with the other constituents, with the result that this phase relation is disturbed and an in-phase component of oscillation develops. It is this in-phase component of the electron motion which is responsible for the dissipation of electromagnetic energy in the plasma. Because of the different masses of the electrons and the heavier particles with which they collide, an electron loses only an extremely small fraction of its energy in a collision. (We assume, of course, that the energy of the electron is too small to excite the internal energies of the atoms) When all collisions are elastic, the transfer of energy from electrons to the other gaseous constituents is very poor. However, the momentum of the electrons is changed in the collisions, and it is this momentum transfer which is significant. It enables us to understand why the temperature of the electron gas can rise significantly above those of the heavier constituents.

Microwaves then undergo attenuation in plasmas (whether immersed or not immersed in magnetic fields); they also undergo changes in their velocity of propagation because of the oscillatory movement of the electrons. And it is possible to measure the changing velocity of propagation and the attenuation. Both of these quantities are functions of the total number of electrons and the total number of electron collisions in the plasma. Now, microwave measurement consists in measuring the real and the imaginary parts of the (complex) plasma conductivity.³ This conductivity (σ_c) is equal to $\sigma_r + j\sigma_i$. Since both parts are functions of the electron density, we may write:

$$\sigma_c = \frac{N_e e^2 [\nu - j\omega]}{m[\nu^2 + \omega^2]}$$

where

N_e = the number density of the electrons

e = charge of the electrons

m = mass of the electrons

ν = total collision frequency of the electrons

ω = signal frequency

$j = \sqrt{-1}$

³ See for instance: H. Margenau, Phys. Rev. 69, 508 (1946) and J. M. Anderson and L. Goldstein, Phys. Rev., 100, 1037 (1955) and references.

Now when ν^2 is much smaller than ω^2 , the formula can be further simplified. The real part of the conductivity which is responsible for the dissipation is given by

$$\sigma_r = \frac{N_e e^2 \nu}{m \omega^2}$$

And similarly the imaginary part is given by:

$$\sigma_i = \frac{N_e e^2}{m} \cdot \frac{\omega}{\omega^2} = \frac{N_e e^2}{m \cdot \omega}$$

The ratio of the real to the imaginary part is therefore ν over ω . This ratio can easily be measured in plasmas; and, since we know the exact signal frequency, we can arrive at the collision frequency of the electrons.

However, we must remember that the electron collision frequency is complicated by the fact that the electrons collide not only with molecules but also with ions and with one another. Since microwaves can detect only electron collisions that involve momentum transfer, they cannot yield information on electron-electron interactions in the plasma, since the total momentum is conserved in the electron gas.

That leaves electron-ion collisions. What exactly is the significance of these collisions? Remember that the plasmas we are considering contain very few ions compared with neutral molecules; that is, the degree of ionization of the gas is very low. Let us look at Figure 9a. Here we have again the situation of a continuous wave sensing a helium plasma when a disturbance is introduced (i.e., at 1b). Now, there is a certain time constant associated with both the rise and fall of the disturbance. When the disturbance stops, the heated electron gas cools off or relaxes. These disturbances, as I have previously made clear, are observed mainly when electrons interact with molecules. Now look at Figure 9b. Here the disturbance has been introduced at an earlier time, during the plasma decay where we reach a somewhat higher degree of ionization in the plasma. When the disturbance starts, the attenuation of the sensing signal decreases before it increases. What this means is that when we have enough ions, the electron-ion collision frequency will play a part until a certain electron temperature is reached.⁴ Once this temperature has been reached, we have to deal only with electron-molecule collisions. In the example we are considering, there is a relaxation when

⁴ The electron-ion collision frequency ν_{ei} is an inverse function of the three-half (3/2) power of the electron temperature. The electron-molecule collision frequency in helium, the example shown, varies as the one-half (1/2) power of the electron temperature. So the total collision frequency varies as $\nu_{total} = \nu_{em} + \nu_{ei} = AT_e^{-3/2} + BT_e^{1/2}$.

Figure 9a

Figure 9b

the disturbance is stopped and everything begins to go back to normal. The double trace at the relaxation (2a, 2b) shows, incidentally, that the electrons are cooling off, back to room temperature, and are going back through the same low temperature range at which the electron-ion collision effect again becomes significant and thus is made visible by the sensing wave.

In order to estimate the degree of ionization at which the electron collision frequency with ions (ν_{ei}) becomes of the order of or larger than that with neutral molecules in the weakly ionized gases dealt with here, we may write separately the relation between the appropriate collision frequency and the collision cross sections. Thus,

$$\nu_{em} \approx Q_{em} N_m \bar{v}_e \quad \text{and} \quad \nu_{ei} \approx Q_{ei} N_i \bar{v}_e$$

where N_m and N_i are the number densities of the neutral molecules and ions respectively, $\bar{v}_e$ is the mean velocity of the electrons, and the Q 's are the momentum transfer collision cross sections of the molecules (em) and ions (ei) respectively.

For $\nu_{ei} \approx \nu_{em}$ or $\frac{\nu_{ei}}{\nu_{em}} \approx 1$, we have

$$\frac{\nu_{ei}}{\nu_{em}} \approx 1 \approx \frac{Q_{ei}}{Q_{em}} \cdot \frac{N_i}{N_m}$$

Since $\frac{N_i}{N_m} \approx \delta$, we see that for a low value of $\delta \left(\delta \approx \frac{Q_{em}}{Q_{ei}} \right)$, the ion collision frequency plays

an equal role with the neutral molecule collision frequency in a plasma.

Now the magnitude of these cross sections depends upon the range of the forces which operate between the interacting particles, electrons with molecules, and electrons with ions. Speaking very roughly, the range of the forces governing the electron-neutral molecule interaction is hardly longer than molecular dimension; the cross section is of the order of $\pi \times (10^{-8} \text{ cm})^2$. The range of the coulomb force for binary collisions in the plasma is however very much longer and may be extended to the so-called Debye length (D). So the Q_{ei} may be of the order of $\pi D^2 \text{ cm}^2$. Now the Debye shielding distance (D) for $n \approx 10^{12}$ and $T_e \approx 300^\circ \text{ K}$ is approximately 10^{-4} cm . Hence $D^2 \approx 10^{-8}$ and

$$\delta \geq \frac{\pi (10^{-8})}{\pi \cdot D^2} \approx \frac{10^{-15}}{10^{-8}} \approx 10^{-7}$$

Thus for helium plasmas with $N_e \approx 10^{12}$ and $T_e \approx 300^\circ\text{K}$, $\delta_{\min} \approx 10^{-7}$.
 For $\delta \gg \delta_{\min}$, $\nu_{ei} > \nu_{em}$.

In Figure 10 we see calculated values for the sum of electron-ion and electron-molecule collisions for various degrees of ionization in helium, that is, for various charge densities and various pressures. (Note that in this diagram the direction of increase in the collision frequencies is downward). If we heat the electrons with the microwave signal in a low-temperature helium plasma of adequate electron density, we increase both the electron temperature and as a result the transparency of the plasma. In other words, increasing the electron temperature decreases the number of electron-ion interactions. This fact is now well known to people who are working with the so-called "hot plasmas"; they have learned that the hotter a plasma gets, the fewer the interactions between the constituents. For this reason also, it is not possible to heat a plasma with any efficiency beyond a certain temperature, say above 10^6K , by heating the ionic constituents through the intermediary of the electron gas. So you see, these low-temperature experiments show rather neatly the behavior of plasmas at very high temperatures.

The calculated effects just mentioned are shown in Figure 11. You can see the disturbing signals (narrow pulses) introduced into the plasma at various power levels and also the wanted signal (wider pulse) both before and after the introduction of the disturbance. Note how the wanted signals increase in amplitude when they sense the disturbance. When the electron temperature becomes high enough to eliminate electron-ion effects, leaving only electron-molecule effects, the amplitude of the transmitted wanted signal decreases. After we have stopped the disturbance, the electron gas cools off and everything returns to normal as indicated by the computation.

An interesting thing about these studies is that we can determine the rate at which energy can be transferred from a hot electron gas to heat a cool gas of ions in a plasma. We have determined the formulae for heating both cool ions and electrons with hot electrons; they are shown below:

$$\frac{dT_e}{dt} = -\frac{1}{\tau_{ei}} (T_e - T_i) - \frac{1}{\tau_{em}} (T_e - T_m), \text{ where } T_i \equiv T_m \quad (1)$$

$$\tau_{ei} = \left(\frac{M_i}{2m} \right) \frac{3\sqrt{m} k^{3/2} T_e^{3/2}}{4\sqrt{2\pi} e^4 N_i \ln \left\{ \frac{k^{3/2} T_e^{3/2}}{N_i^{1/2} e^3} \right\}} \quad (2)$$

$$\tau_{em} = \left(\frac{M}{2m} \right) \frac{3\sqrt{\pi m}}{8\sqrt{2} qN\sqrt{kT_e}} \quad (3)$$

$$T_e(t) = T_{m,i} - \left(T_{m,i} - T_e(o) \right) e^{-t/\tau}, \quad (4)$$

where $T_i = T_m \triangleq T_{m,i}$ and $T_e(t) - T_{m,i} \ll T_e(o)$

$$\frac{1}{\tau} = \frac{1}{\tau_{ei}} + \frac{1}{\tau_{em}}; \text{ if } \tau_{ei} \ll \tau_{em}, \text{ then } \tau \approx \tau_{ei}; \text{ or if } \tau_{em} \ll \tau_{ei}, \text{ then } \tau \approx \tau_{em} \quad (5)$$

$$P_a(T_e) = \int_v^2 \sigma_r(T_e) dv; \sigma_r(T_e) \approx \frac{ne^2 \nu(T_e)}{mw^2}; \nu(T_e) = \nu_{em}(T_e) + \nu_{ei}(T_e) \quad (6)$$

$$P_a(t) = P'_a - \left(P'_a - P_a(o) \right) e^{-t/\tau}, \quad (7)$$

restricted to $T_e(o) - T_{e,m} \ll T_e(o)$, and uniform plasma.

Equation 2 shows the characteristic relaxation time (τ_{ei}) of electrons against ions, that is, the case of using the warm electron gas to heat a cool gas of ions. This relaxation time, you will notice, is a function of the ion mass and is directly proportional to $T_e^{(3/2)}$.

Below is shown the computed values of the τ 's for neon at a pressure of about 3 millimeters of mercury -- a rather high pressure, particularly for people working with hot plasmas.

Neon gas	$N = 10^{17}$ atoms per cm^3
3 mm Hg Pressure	$N_i = 5 \times 10^{11}$ ions per cm^3
$T_e \approx T_i = T_m = 300^\circ K$	$(N/N_i) = 2 \times 10^5$ atom per ion
$q(T_e) \approx 0.6 \times 10^{-16} cm^2$	Assume $M_i = M$

$$\tau_{em} = 120 \text{ microseconds}$$

$$\tau_{ei} = 11 \text{ microseconds}$$

$$\text{Here } \tau_{ei} \ll \tau_{em}$$

$$\text{Thus } \tau = \left(\frac{1}{\tau_{ei}} + \frac{1}{\tau_{em}} \right)^{-1} \approx \tau_{ei}$$

Despite the low degree of ionization (2×10^5 atoms per ion), the relaxation time of the electrons is at least 10 times faster with ions than with molecules. This is due to the fact that electrons interact with ions with coulomb forces of considerably long range, whereas they interact with atoms with forces of very short range, as we have mentioned before. Experimental results on these experiments are shown in Figure 12.

Figure 10

Figure 11

Characteristic Time for Equipartition of Energy through Electron-Ion Collisions versus Ion Concentration in Neon Plasma.

Figure 12

I would now like to devote a little more attention to electron-electron effects. Since both electron-ion and electron-electron effects result from the long range of the coulomb forces, as we have seen, charge effects may predominate even in plasmas containing many more neutral molecules than charges. This opens the door to another method of studying electron-electron effects. If we have a hot electron gas in the presence of a cool ion gas, we know the time it will take for the ion gas to warm up at the expense of the electron gas. From the mass ratios, we can also easily deduce how rapidly a hot electron gas can be cooled by a cool electron gas. We have performed a direct experiment to demonstrate the effect. Before describing this experiment, however, I would like to draw a simple analogy to illustrate the electron-electron effects. If we heat a metallic rod someplace in the center, the heat will obviously flow outward. A rod-shaped plasma will behave in essentially the same manner. Imagine that by means of microwaves we have heated such a plasma locally in a very small volume. The temperature of the electrons will, of course, be raised there selectively. Now because electrons have equal masses, electron-electron interactions are much more efficient in energy transfer than electron interactions with the heavier ions or molecules. Heat will flow out from the heated region mainly in the electron gas of the plasma, because, despite the low degree of ionization, the "warm" electrons can transfer energy to "cooler" electrons much more readily than they can to the heavier constituents.

Here is how the experiment is performed (see Figure 13). Starting with an elongated isothermal plasma that crosses two wave guides, we introduce a disturbing heating-wave pulse in either or both of the waveguides and observe its effect in both waveguides. As we have shown earlier a most sensitive way of detecting an electron temperature increase in the plasma is the observation of the quenching of the afterglow.

Take, for example, Figure 14. Here we look at the light intensity of the decaying plasma in the part of the waveguide to which the heating pulse has been applied. Notice that in the region of heating there is no detectable delay between the disturbance and the change in light intensity. In Figure 15 we observe the plasma at various distance from the heated region. At 0.5 centimeter there is a delay; at 1.5 centimeters, the delay is longer, and so on. Because the delay points constitute a parabola, as illustrated by Figure 16, it is very easy to compute the thermal conductivity by a transient method and consequently the electron-electron interaction in such a plasma.

Figure 17 shows a steady-state condition at various distances from the heated region. From these we can compute the thermal conductivity of a plasma in a different way (steady-state method). Figure 18 shows such results obtained by these two methods. Figure 19 is a curve on which both measured and computed thermal conductivities have been plotted. The two are in agreement within the range of experimental and theoretical errors.

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18

Figure 19

I would like to conclude by telling you how an electron beam or a cold plasma can be used as an electronic thermometer on a hot plasma, although the experiment has not yet been made. Suppose that we have a plasma in a tube and that we propagate a shock wave through it. In a lateral tube we have placed a cold plasma, that is, a plasma that has decayed to a low temperature. When the shock front passes, the cold plasma is in contact with the shock front for only a short while. But during the "contact", heating of the cold plasma occurs at the point of contact. From there heat flows up into the electron gas of the cold plasma. The first experiments of this sort are being now attempted at Illinois. This same principle could be extended by using an electron beam instead of a cold plasma. This can be done because practically only the electrons are responsible for heat flow; ions or molecules are simply not needed. Besides an electron beam can be very cold, (as cold as 1 or 0.1°K). (In a fast electron beam practically all of the motion is ordered, and there is little or no temperature motion). If such an electron beam were to contact a plasma, heat would flow with a known heat conductivity into the beam. A noise signal detected along the beam would serve as an indication of the temperature of the hot plasma with which the electron beam was in contact.