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An Experimental Study of Gyro Interaction in the Ionosphere, at Oblique Incidence

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This paper describes further experiments on the interaction between a gyro disturbing wave and an obliquely incident wanted wave in the night time lower *E* region. The results fully confirm those reported some years ago concerning the enhanced effect at the gyrofrequency. Average values of $G\nu$ of about 800 sec^{-1} were obtained, with a height variation consistent with a scale height of the order of 8 km. The effects of multipath interference and the problem of the energy loss factor G are described in the appendixes.

1. Introduction

This paper describes an experimental study of gyro interaction in the ionosphere carried out in Australia several years ago by the author, R. A. Smith, and V. A. Bailey. Some results in an earlier part of this study were reported briefly by Bailey et al. [1952]. We present here an account of further experiments, with improved precision, that were made following this early work. The experiments were designed primarily to test the gyro resonance effect predicted by Bailey, and were carried out at night using a pulsed gyro disturbing wave and an obliquely incident wanted wave.

The resonance effect in gyro interaction depends in part on the well-known resonance in the absorption of the extraordinary component of the disturbing wave at the gyrofrequency and in part on the path of the wanted wave in the disturbed region. The phenomenon was analysed in detail by Bailey [1937, 1938]. Although the full mathematical description is somewhat complex, the basic physical ideas can be presented quite simply as follows. Because of the very high absorption near the gyrofrequency the energy in the extraordinary component of the disturbing wave is practically all absorbed after it has traveled some 6 or 7 km upward into the nighttime ionosphere. The region of the ionosphere in which the electron energy is perturbed thus consists of a relatively thin horizontal slab, above the disturbing transmitter, of fairly large horizontal extent. The increase in electron energy within this slab is much greater than that which would be produced in the same region by a wave of the same power whose frequency is far removed from the gyrofrequency. The way in which the energy I absorbed per unit volume in the slab varies with frequency and with height in the slab is shown in figure 1. At the lower heights the curves have a maximum at the gyrofrequency; at greater heights there is a subsidiary minimum here because the wave has been severely attenuated before it reaches these heights. The curves in figure 1 have been computed, for purposes of illustration only, for a typical model of the lower nighttime ionosphere in which the electron density N and collision frequency ν vary with height as

$$N=N_0 \exp(0.8h) \text{ and } \nu=1.2\times10^6 \exp(-0.16h),$$

where h is the height in kilometers measured from an arbitrary base height—the bottom of the slab—at which N_0 is taken as 1 electron cm^{-3}.

When a wanted wave travels horizontally through the slab at a given height, the modulation that it acquires over an element of its path length varies with disturbing frequency in the same manner as the curve in figure 1 that corresponds to that height. Because the wanted wave takes a finite time to pass

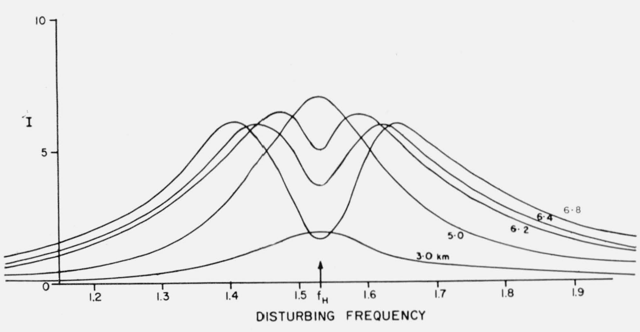

FIGURE 1. *The energy I (in arbitrary units) absorbed per unit volume of the ionosphere as a function of the frequency, in Mc/s, of the disturbing wave in the vicinity of the gyrofrequency, computed for a model nighttime ionosphere, at various heights above the base of the ionosphere.*

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through the disturbed region the phase of the modulation acquired over each successive element of path changes as the wave proceeds. But provided that the time to traverse the whole path is small compared with the time variation of the collision frequency, this phase change will be small and may be neglected. Further, the path within the slab is not exactly horizontal in practice but is slightly concave downwards and so the wave acquires its modulation over a narrow range of heights with the slab. The result of this is that the impressed modulation corresponds to average values of the ionospheric properties over a narrow height range, rather than to values at a sharply defined height. For the very obliquely propagated wanted wave used in the experiments this height range is probably two or three kilometers.

From the foregoing it will be seen that a large amount of modulation can be impressed on a wanted wave by a gyro disturbing wave when the wanted wave travels nearly horizontally through the slab and so has a long path length in the disturbed region. It is this combination of a gyro disturbing wave, with its concentrated and strongly frequency-dependent effect, and an appropriate trajectory for the wanted wave, that gives rise to the "resonance" in gyro interaction. This situation should be contrasted with those in which (i) an oblique wanted wave is reflected well above the slab and (ii) a vertically incident wanted wave is reflected above the height where most of the energy has been absorbed from the disturbing wave. In neither of these situations would one expect to observe a large effect at the gyrofrequency or a marked dependence on disturbing frequency.

2. Experimental Details

In the experiments described here the wanted transmitter was located at Brisbane and radiated a continuous wave. The wanted wave was received at Katoomba, west of Sydney and 720 km south of Brisbane. The disturbing transmitter was located at Armidale on the mid-point between wanted transmitter and receiver. It radiated rectangular pulses on a frequency that was variable about the gyrofrequency. Details of the transmitters are as follows:

Wanted transmitter: Continuous wave, frequency 590 kc/s, power 10 kW. *Disturbing transmitter:* Pulse length 1 millisecond, pulse repetition frequency 40 per second, peak power 36 kW, frequency variable in steps of 30 kc/s from 1390 to 1690 kc/s, half-wave dipole antenna. Local gyrofrequency at height of 90 km is 1530 kc/s, magnetic dip angle is 60°.

Observations were made between 0100 and 0220 hours. The bandwidth of the wanted-wave receiver was sufficiently wide to avoid distorting the pulse modulation acquired by the wanted wave. Automatic gain control was used in the receiver and a meter was incorporated in the A.G.C. circuit to indicate the strength of the received signal.

The disturbing transmitter was switched on for one minute on each of the 13 frequencies from 1390 to 1690 kc/s in succession, with a blank interval of one minute between each disturbing radiation. During this blank interval the wanted carrier was modulated for 30 seconds at its transmitter with an 80 c/s sinusoidal signal to a depth of 5 percent. This sinusoidal modulation provided a calibration for the measurement of the depth of the modulation impressed on the wanted carrier by interaction.

The rectified output of the receiver was applied to the vertical deflection plates of an oscilloscope and the length of the trace photographed on horizontally-moving film. Examples of the records obtained are shown in figures 2a and 2b. Records of this type yielded the amplitude of the impressed modulation as a function of the disturbing frequency.

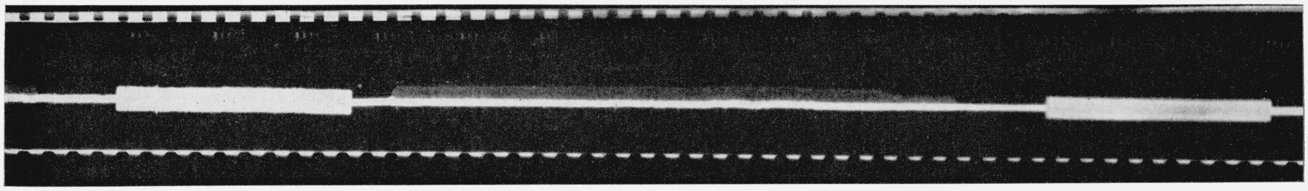

FIGURE 2a. *The amplitude of modulation impressed on wanted wave (long portion) and of the calibration sinusoidal modulation (short portions), recorded on moving film.*
This record is typical of those obtained when fading was absent.

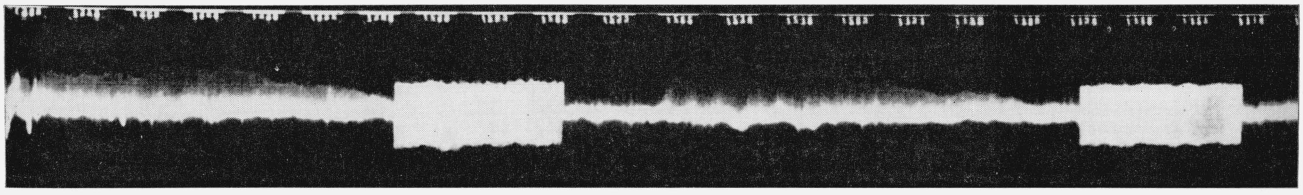

FIGURE 2b. *Similar record to figure 2a obtained when multipath fading occurs.*

The rectified output was also displayed on a second oscilloscope with linear sweep and photographed at intervals of 3 or 6 seconds. The signal strength was also recorded on this photograph. Figure 3 is a typical picture of the display. The upper trace shows the increase and decay of the incremental absorption of the wanted wave and hence of the electron collision frequency. The shape of these pulses was used to obtain the time constant for the change in collision frequency. The lower trace shows the disturbing pulse which was received directly on a separate receiver after reflection from the ionosphere, together with numerous multiple reflections. This trace plays no essential part in the observations and was used merely to monitor the disturbing transmitter.

The disturbing transmitter was correctly matched to the antenna at each frequency in turn, and the antenna current measured with calibrated meters. The various matching and coupling settings at the transmitter had been determined by prior calibration. The power actually radiated was calculated from the antenna current and the measured radiation resistance at each frequency.

3. Experimental Resonance Curves

Because of the effects of multipath fading, meaningful measurements of the amplitude of interaction can only be made when the received wanted wave consists solely of the ray that has been reflected in the vicinity of the disturbed region. Fluctuation of the amplitude of the rectified pulse on the wanted wave and occasional inversions of the pulse occurred sporadically for more than one third of the total observing time. These fluctuations were always accompanied by a decreased and fluctuating signal strength of the wanted wave. When the wanted signal remained strong and reasonably constant (free of the deep fading characteristic of multipath fading) the amplitude of the rectified pulse was remarkably constant and records like those in figure 2a were obtained. On the other hand, when the signal strength fell or fluctuated, the records were like those in figure 2b.

For reasons given in appendix 1 it was concluded that when the records were like those in figure 2a, which were obtained when the wanted wave was strong and steady, the only ray present was that which had been reflected once in the E region. Records of this type alone were selected for amplitude measurement. The depths of impressed modulation obtained at each frequency were normalized to a standard disturbing power of 36 kW and plotted as a function of disturbing frequency. (Some measurements of the depth of modulation were also made on records of the type of figure 3. These agreed well with the main measurements.)

During the 23 minutes required to traverse the range of disturbing frequencies some multipath fading invariably occurred. In fact, on some nights virtually no useful amplitude measurements were obtainable. It is usually not possible to combine data obtained at widely separated times, because minor changes in the gradient of electron density or in reflection height produce changes in the detailed shape of the resonance curves. Nevertheless, there were sufficient occasions when complete, or almost complete, resonance curves were obtained. Examples of such curves are shown in figure 4.

It is seen that these curves exhibit the predicted variation with disturbing frequency and that a relatively large depth of modulation, of the order

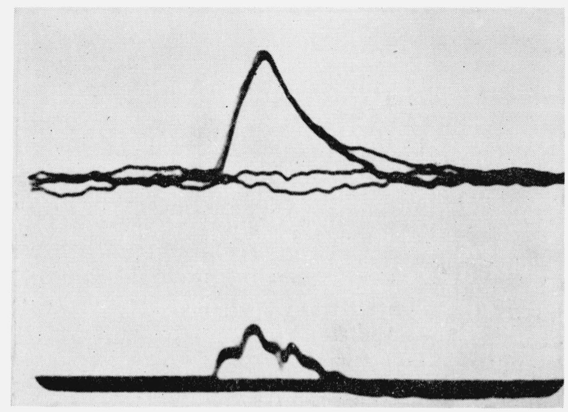

FIGURE 3. *Photograph of the pulse modulation impressed on the wanted wave by a rectangular disturbing pulse.*
The lower trace shows the directly received disturbing pulse and its multiple echoes.

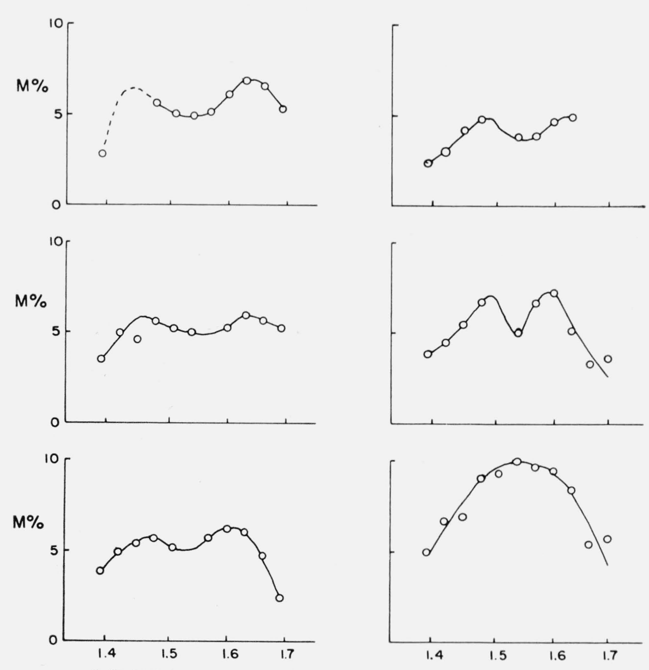

FIGURE 4. *Experimental curves obtained on various occasions, showing the depth of modulation impressed on the wanted wave as a function of disturbing frequency.*

of 5 percent, is produced with a disturbing power of 36 kW. They thus confirm in detail Bailey's prediction of the resonance effect. The same conclusion was reached in the brief report by Bailey et al. [1952] of the earlier measurements. The earlier measurements were made on the amplitude of individual pulses, like that in figure 3, and it was not always as easy to recognize the occurrence of multipath fading as it was in the present experiments.

4. The Time Constant $1/(G\nu)$

According to the conventional theory of wave interaction [Bailey and Martyn, 1934; Bailey, 1937, 1938] the time constant describing changes in electron collision frequency ν is given by $1/(G\nu)$, where G is a constant related to the mean fractional loss of energy by an electron in a collision with an air molecule. Thus the change in collision frequency produced at a point in the ionosphere by a rectangular disturbing pulse of duration T varies with time as

$$1-e^{-G\nu t} \text{ for } 0<t<T$$

and as

$$e^{-G\nu t} \text{ for } T<t<\infty.$$

The change in absorption of the wanted wave varies in the same manner. The pulses of modulation impressed on the wanted wave should therefore consist of an exponential rise and decay. This has been found to be the case, as illustrated in figure 3.

A number of the clearest photographs of pulses in which the noise level was low were very carefully measured and the shapes were found to be indistinguishable from a pure exponential. Also, no significant difference in exponent could be detected between pulses obtained in the absence or presence of fading, including such severe fading that the rectified pulse was inverted. It is shown in appendix 1 that no difference is to be expected and for this reason the measurement of $G\nu$ was not restricted to those occasions when there was no fading. Of course, it can occasionally happen that the relative amplitudes and phases of the interfering components are such that the resultant wave is over-modulated, but this produces a characteristic distortion of the pulse shape which is very easily recognized. It occurred on only a very few occasions.

In order to measure the values of $G\nu$ from a large number of photographs, an exponential pulse was generated from a rectangular pulse of 1 millisecond duration and of adjustable amplitude, by means of a simple resistance-capacitance network. The generated pulse was displayed on an oscilloscope and was matched in amplitude and shape to that in the photographic negative. $G\nu$ was then obtained from the corresponding value of RC. The main limitation on accuracy in the determination of $G\nu$ arises from the presence of noise on the wanted signal. The uncertainty in individual measurements of $G\nu$ is of the order of 10 percent.

Values of $G\nu$ were obtained from all records in which the noise level was sufficiently low, irrespective of whether the occurrence of fading prevented useful amplitude measurements from being obtained. The measured values of $G\nu$ lay between 650 and 1000 $\sec^{-1}$ and within these limits there was considerable scatter at any one disturbing frequency. However, following the suggestion of R. A. Smith, when the values of $G\nu$ were averaged separately for each disturbing frequency a variation of $G\nu$ with disturbing frequency was found. This is shown in figure 5. Since the path of the wanted wave is independent of disturbing frequency we conclude that this effect is associated with the fact that a larger fraction of the disturbing energy is absorbed in the lower part of the slab at the gyrofrequency than at disturbing frequencies removed from the gyrofrequency.

We can make an estimate of the order of magnitude of the scale height from this. By replotting the data in figure 1 to show the variation with height of the energy absorbed per unit volume for various constant frequencies, it is found that its maximum (or mean) value at the gyrofrequency occurs at a height approximately 1 kilometer below that of the maximum (or mean) value for frequencies that are ± 150 kc/s from the gyrofrequency. The scale height H is

$$H=-\nu\Delta h/\Delta\nu.$$

From figure 5 we have that $\Delta\nu/\nu\sim 1/8$ and, from the above, $\Delta h\sim 1$ km. This gives $H\sim 8$ km, within a factor of about 2. The effect seen in figure 5 is thus consistent with the known height dependence of the collision frequency at altitudes near 90 km.

With the assumption that the time constant can be identified with $1/G\nu$, we adopt the value $G=1.70\times 10^{-3}$ suggested in appendix 2. From figure 5 we see that $G\nu=880$ when the disturbing frequency is very close to the gyrofrequency. This yields $\nu=5.2\times 10^5$ for the collision frequency. There is some uncertainty about the height that this corresponds to but it must be where the electron density has a value of 100 to 400 cm^{-3} and is probably close to 90 km. This value of collision frequency may be

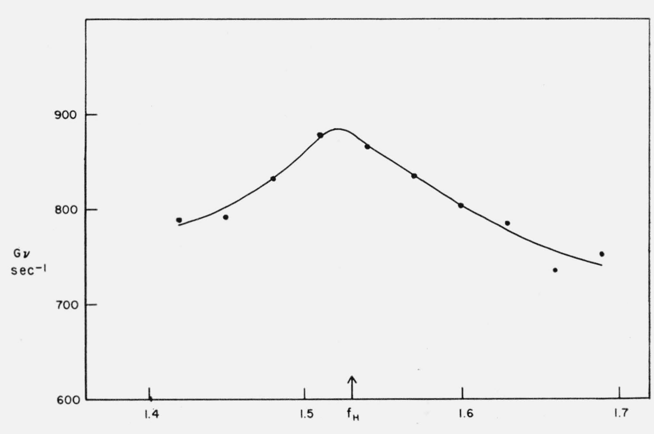

FIGURE 5. *Variation of* $G\nu$ *as a function of disturbing frequency.*

compared with that obtained by extrapolating Kane's [1959, 1962] data to 90 km, which is $\nu=5.0\times10^5$ using the Appleton-Hartree magneto-ionic theory or 2.4×10^5 using the generalized magneto-ionic theory. The agreement suggests that the assumption concerning the electron energy loss, discussed in appendix 2, is at least approximately correct.

5. Appendix 1. Effects of Multipath Interference Fading

In oblique incidence transmission a wave may propagate from transmitter to receiver by several different paths. For the experiments described here it is necessary to examine the result of the simultaneous arrival at the wanted receiver of a wave that has undergone a single reflection in the vicinity of the disturbed part of the E region and other waves, such as those reflected once or more from the F or E_s layers, that have not traversed the disturbed part of the ionosphere. The ray that traverses the disturbed region acquires modulation there by interaction; the other rays remain unmodulated. Interference between the modulated and unmodulated continuous waves produces a resultant modulation whose amplitude and phase depend on the relative amplitudes and phases of the two components. The effects of simultaneous reception of modulated and unmodulated rays can be seen by considering what happens when their RF carriers arrive (i) in phase, and (ii) 180 degrees out of phase.

When the carriers are in phase they add, and the modulation depth on the resultant is less than the true depth of modulation impressed on the modulated component by interaction. However the phase of the modulation, or for pulses, the pulse shape, is unchanged by the presence of the unmodulated component.

When the carriers are antiphased they subtract. There are then three possibilities:

(a) The amplitude of the unmodulated component is less than the amplitude of the modulated component at the modulation troughs: The resultant modulation depth is greater than that on the modulated component alone, but the phase or shape of the modulation is unchanged.

(b) The amplitude of the unmodulated component is greater than that of the modulated component at the modulation peaks: The resultant modulation depth may take any value. The phase of the modulation is shifted by 180 degrees. For pulse modulation this implies that the rectified signal will be inverted but the shape of the pulses will be otherwise unchanged.

(c) The relative amplitudes of the components are intermediate between these in (a) and (b): The resultant modulation depth exceeds 100 percent, so that the modulation is distorted.

It is thus seen that the true depth of the modulation impressed on the wanted wave can only be obtained when the wanted wave consists solely of the ray that has been reflected in the vicinity of the disturbed region. On the other hand, except when the modulation is distorted [Case (c)], the presence of some unmodulated component does not prevent meaningful measurements of the modulation phase, or pulse shape, from being made.

It is interesting to note that Ratcliffe and Shaw [1948] measured the dependence of the amplitude and phase of sinusoidal modulation impressed on the wanted wave as a function of modulation frequency of the disturbing wave. They found that the phase measurements agreed much better with the theory than did the amplitude measurements and were unable to explain this. The observation could well be accounted for if from time to time in their experiments some significant amount of unmodulated wanted wave was received.

6. Appendix 2. The Electron Energy Loss Relation and the Value of G for Air

The problem of the loss of energy by electrons in collisions with air molecules has received considerable attention in recent years but it cannot yet be regarded as satisfactorily resolved.

It is desirable, however, to attempt to interpret the values of the time constant measured from the changes in absorption of the wanted wave. This will be done by retaining the original hypothesis that the mean loss of energy by an electron in a collision is proportional to the difference between the mean energy of the electrons and the mean energy of the air molecules. When this assumption is made the time constant is identified as the quantity $1/(G\nu)$, where G is the constant of proportionality in the above hypothesis.

Information about the hypothesis and the value of G, if it is in fact a constant, can be obtained from laboratory experiments on the diffusion and drift of low energy electrons in gases. Unfortunately, the laboratory experimental data for *air* only extend down to mean electron energies that are about six times greater than thermal and extrapolations or other assumptions must be made in order to obtain values for the lower energies relevant to ionospheric studies. We introduce the following symbols used in diffusion and drift studies:

Q_0 = mean energy of agitation of a gas molecule
Q = mean energy of agitation of an electron
$k=Q/Q_0$
ΔQ = mean energy lost by an electron in a collision with a gas molecule
$\lambda=\Delta Q/Q$ = mean fraction of its energy lost by an electron in a collision
Z/p = ratio of applied electric field to gas pressure.

The quantity k represents the mean electron energy expressed in terms of the energy of a molecule as unit. The product λk represents the energy lost by an electron per collision, in the same units, and is directly related to the drift velocity of electrons in the gas. For a given gas k and λk are each functions of Z/p alone and may be obtained from separate laboratory experiments. By associating correspond-

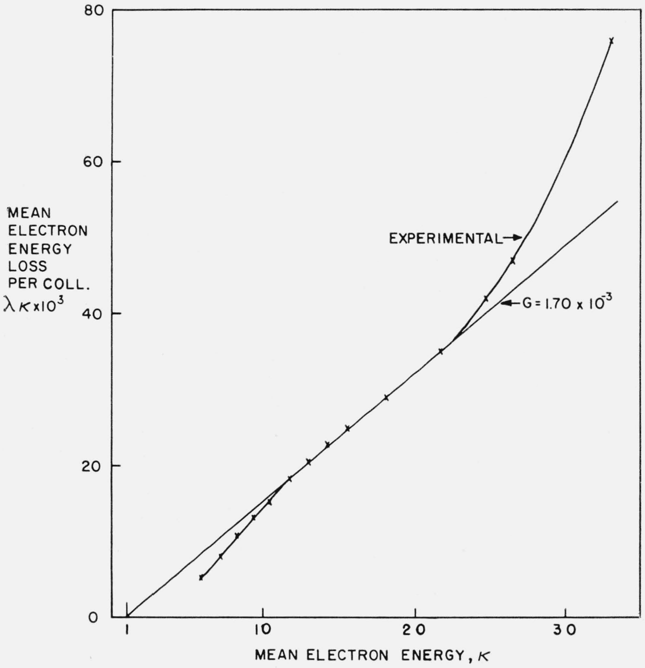

FIGURE 6. *Experimental values for air of the mean energy lost by an electron per collision, λκ, as a function of the mean electron energy, κ; after Crompton et al. (1953).*

The energies are in terms of the mean molecular energy as unit. The straight line corresponds to the hypothesis that the electron energy loss is proportional to the difference between the electron energy and the molecular energy.

ing values of k and λk measured at the same Z/p one obtains λk as a function of k. The most reliable values of k for air are those obtained by Crompton, Huxley, and Sutton [1953] and, of drift velocity and λk, those obtained by Nielson and Bradbury [1937]. The values of λk as a function of k, for the lowest energies, are plotted in figure 6. The lowest energy represented here is $k=5.9$, whereas the region of interest for ionospheric effects is near $k=1$.

The original hypothesis of Bailey and Martyn [1934], based on measurements in air by Townsend and Tizard [1913] and on the theoretical behavior for elastic collisions, is that the mean loss of energy by an electron in a collision is proportional to the difference between the mean energy of the electrons and that of the gas molecules. The hypothesis may be written as

$$\Delta Q = G(Q - Q_0)$$

when G is the constant of proportionality. This is equivalent to

$$\lambda k = G(k-1).$$

If the hypothesis is correct the graph of λk against k should be a straight line which intersects the k axis at $k=1$. In figure 6 the experimental points from $k=21.7$ to $k=10.5$ lie very closely on a straight line whose extension meets the k axis at $k=1$. The slope of this line yields for G the value of 1.70×10^{-3}. (Points for k greater than about 22 lie above the line but this effect is presumably associated with electronic excitation and is not relevant to our discussion.) The fact that the five points below $k=10.5$ fall increasingly below the line have led to serious doubt about the validity of the G hypothesis for air. It may be noted that the greatest deviation from the line, shown by the lowest point, would correspond either to a deviation of 20 percent in the value of the drift velocity or a deviation of 45 percent in the value of k. Whether the results of figure 6 either establish or disprove the G hypothesis is far from obvious, as indeed also is the more fundamental question of whether there is any thermodynamic or other reason to expect the hypothesis to hold for gases other than the rare gases.

Data for nitrogen are available for considerably lower energies than those for air and arguments have been given that suggest that at very low energies the loss of energy by electrons in collisions with oxygen molecules is much less than those with nitrogen, so that the energy loss in air at very low energies may be estimated from the experimental results for nitrogen. On the other hand the results of Brose [1925] and of Healey and Kirkpatrick [1939] for oxygen at $k\sim6$ indicate that at this energy the energy loss is much greater in oxygen that nitrogen. There is still uncertainty about these questions. If, for simplicity, one adopts the G hypothesis for air as a tentative approximation, the best value for G would appear to be 1.70×10^{-3}.

Finally, it will be recalled that there was a suggestion some years ago that the energy loss in air was proportional to $(Q-Q_0)^2$. This relation was subsequently withdrawn because it was considered to conflict with deductions from the magneto-ionic theory. This discarded hypothesis is only mentioned here because it has been revived in a recent report. A simple argument shows that the relation cannot be true in the vicinity of $k=1$. Because the velocity distribution of each set of particles, electrons and molecules, is Maxwellian or very nearly so near $k=1$, the suggested relation is equivalent to the statement that the electron energy loss (or transfer of thermal energy) is proportional to $(T-T_0)^2$ where T is the electron temperature and T_0 is the gas temperature. This implies that the direction of heat flow does not reverse when the temperature difference changes sign, which contradicts the second law of thermodynamics. The rate of energy loss by the electrons must clearly be an odd function of $Q-Q_0$ in the vicinity of $k=1$.

The uncertainty about the dependence of the electron energy loss on the electron energy constitutes one of the most serious problems in the theory of wave interaction. It is directly related to the other outstanding problem of the manner in which electron collision frequency depends on the electron energy.

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7. References

Bailey, V. A. (April 1937a), The motions of electrons in a gas in the presence of variable electric fields and a constant magnetic field, Phil. Mag. **23,** No. 156, 774–791.

Bailey, V. A. (May 1937b), On some effects caused in the ionosphere by electric waves. Part I, Phil. Mag. **23,** No. 157, 929–960.

Bailey, V. A. (Oct. 1938), On some effects caused in the ionosphere by electric waves, Part II, Phil. Mag. **26,** No. 176, 425–453.

Bailey, V. A., and D. F. Martyn (Aug. 1934), The influence of electric waves on the ionosphere, Phil. Mag. **18,** No. 118, 369–385.

Bailey, V. A., R. A. Smith, K. Landecker, A. J. Higgs, and F. H. Hibberd (May 31, 1952), Resonance in gyro-interaction of radio waves, Nature **169,** 911–913.

Brose, H. L. (1925), The motions of electrons in oxygen, Phil. Mag. **50,** 536–546.

Crompton, R. W., L. G. H. Huxley, and D. J. Sutton (1953), Experimental studies of the motions of slow electrons in air with application to the ionosphere, Proc. Roy. Soc. A **218,** 507–519.

Healey, R. H., C. B. Kirkpatrick (1939), quoted on p. 94 of The behaviour of slow electrons in gases by R. H. Healey and J. W. Reed, 1941 (Sydney, A.W.A. Ltd. Australia).

Kane, J. A. (Feb. 1959), Arctic measurements of electron collision frequencies in the D-region of the ionosphere, J. Geophys. Res. **64,** No. 2, 133–139.

Kane, J. A. (1961), Re-evaluation of ionospheric electron densities and collision frequencies derived from rocket measurements of refractive index and attenuation, J. Atmospheric Terrest. Phys. **23,** 338–347.

Nielson, R. A., and N. E. Bradbury (1937), Electron and negative ion mobilities in oxygen, air, nitrous oxide and ammonia, Phys. Rev. **51,** 69–75.

Ratcliffe, J. A., and I. J. Shaw (1948), A study of the interaction of radio waves, Proc. Roy. Soc. A **193,** 311–343.

Townsend, J. S., and H. T. Tizard (1913), The motion of electrons in gases, Proc. Roy. Soc. A **88,** 336–347.

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