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Experiments on the Negative Radiation Temperature
at Cyclotron Resonance in Cold Plasma

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ABSTRACT

The anomalous microwave radiation from a plasma in a magnetic field was observed. The intensity was extremely large compared with that of blackbody and amounted to the power radiated from the plasma in the thermal equilibrium equivalent to 5.5×10^6 °K in the case of Kr and 1.5×10^6 °K in Xe. This radiation occurred very sharply at the cyclotron field, the width being one order smaller than that of normal cyclotron radiation. The radiation was observed in Xe, Kr and Ar plasmas in the pressure range of $p = 1 \times 10^{-1} \sim 5$ mmHg, but not in Ne and He plasmas at any pressure. Further, the radiation was observed when the whole tube was placed in a longitudinal magnetic field, but not when a part of the positive column was immersed in the field.

On the other hand, the theoretical condition for a negative temperature at the cyclotron resonance in a weakly ionized gas was investigated. Then it was discussed whether this anomalous radiation could be interpreted as a phenomenon of the negative radiation temperature.

§ 1. Introduction

In this paper, only an extraordinary wave.¹⁾ propagating perpendicularly to an external magnetic field B , is considered. Then, the resonant radiation of the microwave emission from a plasma in a magnetic field occurs at :

$$\omega^2 = \omega_p^2 + \omega_b^2, \quad (1)$$

where $\omega_p = (e^2 n_e / m \epsilon_0)^{1/2}$ is the plasma frequency, $\omega_b = eB/m$ and ω the resonant frequency. The plasma type radiation, given by Eq.(1), has been discussed theoretically by Gross,²⁾ Bernstein³⁾ and Sitenko et al.⁴⁾ and investigated experimentally by Brown et al.⁵⁾, Miyoshi⁶⁾ and the present authors^{7,8)}. It was reported by Kato⁹⁾ that the oscillation of the two types detected by a probe: the P-type oscillation, given by Eq.(1), and the C-type oscillation, independently of the electron density, given by :

$$\omega = \omega_c = eB/m. \quad (2)$$

Furthermore, the present authors¹⁰⁾ found that the P-type radiation has a harmonic structure, by the measurement of microwave radiation from dc discharge plasma, partly placed in a magnetic field. That is, the resonant radiation occurred not only at $\omega^2 = \omega_p^2 + \omega_b^2$ but also near the cyclotron harmonics, $\omega = \omega_c/n$ (n being an integer) in the case of large discharge current.

On the other hand, when the whole tube inclusive of the cathode is placed in a magnetic field, the following anomalous microwave radiation was observed, together with P-type and C-type radiation. In Xe, Kr and Ar plasmas, the enormously large and very sharp radiation occurred at the cyclotron field ω_c , but not in Ne and He plasmas. Such a radiation was observed only in the pressure range, $p = 1 \times 10^{-1} \sim 5 \text{ mmHg}$, whereas the resonant peaks at cyclotron harmonics (up to the 13th) occurred¹¹⁾ in the lower pressure range ($p \lesssim 10^{-1} \text{ mmHg}$).

Similar phenomena to the latter have been reported by others^{12,13}). As far as the authors are aware, such an enormously large radiation, as mentioned above, has not yet been observed in any experiment, and it is thought to be the phenomenon due to the negative absorption effect, such as theoretically suggested by Twiss¹⁴) and Brown et al.¹⁵).

In the following, the procedure and the results of our experiments will be given in detail. Further, an effect of the negative radiation temperature at cyclotron resonance in a weakly ionized gas will be investigated theoretically and it will be discussed whether this anomalous radiation is ascribed to such an effect.

§ 2. Experimental Apparatus and Procedures

The discharge tube used is shown in Fig. 1. The tube, 13mm in inner diameter, was placed between the pole pieces (225 mm in diameter and 100 mm in gap length) of the electromagnet. An anode was a tantalum disk of 9 mm in diameter and set 38 mm away from a cathode. The indirectly heated cathode consisted of two coaxial hollow cylinders with four spacing walls, 10 mm in outer diameter and 33 mm in length, as shown in Fig.1. Although the magnetic field should be disturbed by the nickel cathode at room temperature, the disturbance in field was not detected by proton-meter or gauss-meter at operating condition of the discharge tube, because of thermal demagnetization of nickel. Therefore, the plasma under study was practically placed in a uniform magnetic field.

The discharge tube was directly connected to vacuum and gas filling system and the gas pressure was set at any values between 10^{-3} and 10 mm Hg for all rare gases. When the whole tube inclusive of the cathode, oxide coated all over, was placed in the magnetic field, the positive column was not stable in appearance. Above the pressure of several mm Hg, a uniform and stationary plasma was

prepared, but a few emitting spots appeared on the cathode and a few beam-like columns were seen in the discharge tube at rather low pressure. The intensities of visible light of the respective beam-like columns changed at random as the discharge current increased. Also, the arc spots on the cathode changed their positions and the beam-like columns rotated as the intensity of the magnetic field was varied. Such an instability could be eliminated by limiting the oxide coating on one section of the inner cylinder.

The measurements of microwave radiation from a plasma, that is a section of the positive column of the dc discharge, were performed by means of 9,000 Mc radiometer¹⁶⁾. The whole discharge tube, inclusive of the cathode, was placed parallel to the static magnetic field B , and passing through a square waveguide (the cross section being $2.29 \times 2.29 \text{ cm}^2$), which was perpendicular to B , with the electric vector in the guide perpendicular to B . Therefore, an extraordinary and plasma wave, propagating transversely to an external magnetic field, might be detected. The radiometer used in this work was operated at the fixed frequency, $\omega/2\pi = 9,485 \text{ Mc}$ with a 5 Mc bandwidth and had an over-all noise figure of 12 db. Since the radiation had a sharp spectral response in our experiments, a waveguide filter was inserted to suppress one of two heterodyne sidebands. Through the second detector which had a square characteristic and the integrating circuit with time constant 10^{-3} sec , the radiation power was displayed on Y-axis of an X-Y recorder. Meanwhile, the field coil current of the magnet or the discharge current of the tube was feeded to X-axis. The block diagram of this experimental method is shown in Fig.2. When the magnetic field was swept at a constant discharge current I_d and the radiometer output was continuously traced on the recorder, the radiation pattern, denoted hereafter by $P(I_d) - B$ patterns, was displayed, in which X- and Y-axis were proportional to the magnetic

field strength B and to the radiated power respectively. In the same way, the radiation patterns denoted by $P(B=0) - I_d$ and $P(B) - I_d$ pattern were recorded by varying the discharge current I_d , being feeded to X-axis, at no magnetic field and at constant field B , respectively. In the figure illustrating the radiation patterns, the zero level of radiation power from plasma was set at the noise power of radiometer itself which was denoted by NL on the left side of each pattern. The radiation pattern, which was recorded at the x db of the attenuator of the radiometer was noted with $G = -x$ db, $G = 0$ db being omitted.

§ 3. Experimental Results

The microwave radiation from the dc discharge plasma, when the whole tube was placed in magnetic field, was different from that, when the magnetic field was impressed on a part of the plasma column¹⁰⁾. In the former case, the behavior of radiation pattern could be classified into the following three types, according to the gas pressure p .

(I) $p \gtrsim 5$ mm Hg

The peak of the radiation pattern shifted to the low magnetic field as a discharge current increased. That is, P-type radiation having the dispersion relation given by Eq.(1), which is similar to the radiation from the plasma in which only a part of positive column was placed in a magnetic field.¹⁰⁾

(II) $p \lesssim 10^{-1}$ mm Hg

In this pressure range it was characteristic that the peaks at cyclotron harmonics as high as 13-th were observed above a certain large discharge current ($I_d \gtrsim 50$ mA). These phenomena were observed indepently of the kind of rare gas and reported in detail elsewhere.¹¹⁾

(iii) $5 \gtrsim p \gtrsim 10^{-1}$ mm Hg

In this pressure range, the radiation patterns were different according to the kind of rare gas. In Xe, Kr and Ar plasmas, the enormously intense radiation was observed at the cyclotron field, whereas in Ne and He plasmas such a radiation was not. Such an anomalous radiation will be described in the following.

In Fig. 3a and b are shown a series of the radiation patterns $(P(I_d) - B)$ recorded for various I_d at a constant pressure. At small currents ($I_d \lesssim 10$ mA) or low electron densities $\omega_p/\omega \ll 1$ there appears the C-type radiation alone, which is situated at the cyclotron field ω_c , independently of I_d . As the current increases ($I_d = 10 \sim 140$ mA), the C-type radiation becomes small and broad, and together with it the weak and broad peak of the P-type radiation comes to be observed at low magnetic field ($\omega_p/\omega < 1$). At last, the peak of C-type disappears in the current range $I_d = 160 \sim 220$ mA. As I_d further increases ($I_d \gtrsim 220$ mA), however, the extremely sharp peak is observed at the cyclotron field ω_c and the amplitude of this peak becomes larger with the increasing I_d . Together with the $P(I_d) - B$ patterns, the $P(B=0) - I_d$ pattern is shown for the same gas pressure, which illustrates the thermal noise power as a function of current I_d at no magnetic field^{17,18}). It may be considered from this pattern, that the radiation power from the plasma attains a saturation value, corresponding to the blackbody radiation, above $I_d = 800$ mA. Therefore, the power of the above-mentioned radiation at ω_c is found to be very large, compared with that radiated from the blackbody. These anomalous resonant radiation at the cyclotron field ω_c which is enormously large in intensity and extremely sharp, will be called N-type radiation hereafter. In a plasma, where only a part of positive column was placed in a magnetic field, the N-type radiation was not observed, but P-type radiation appeared dominantly. On the contrary, when the

whole tube was placed in the magnetic field, the C-type radiation was observed up to the rather large current ($I_d \lesssim 140$ mA) in addition to the N-type radiation.

The way of appearance of the N-type radiation is seen more clearly in Fig.4, which illustrates the $P(I_d) - B$ patterns in the vicinity of ω_c only, with I_d as a parameter. The C-type radiation observed at $I_d = 10 \sim 40$ mA disappears as I_d increases and no peaks are seen in the vicinity of ω_c at $I_d = 60 \sim 100$ mA. However, the sharp peak begins to appear at ω_c when $I_d = 120$ mA and its intensity becomes larger with the increasing I_d . PBB at the right hand side in this figure denotes the power radiated from blackbody at that pressure, which is estimated by the $P(B=0) - I_d$ pattern. With the current I_d swept and the magnetic field fixed to ω_c , the intensity of N-type radiation as a function of current I_d was recorded. Such a pattern ($P(\omega_c) - I_d$) is shown in Fig.5a together with the $P(B=0) - I_d$ pattern. The radiation power from the noise standard which was a fluorescent tube (FL - 6) mounted within a section of X-band waveguide, and inclined at an angle of about 10 degrees to it, is shown for reference. In this pattern, any radiation except N-type should not be observed since a large attenuation is inserted in recording. The intense radiation of N-type is seen in the current range $I_d = 400 \sim 800$ mA. It is shown from these $P(\omega_c) - I_d$ patterns, that the intensity of the N-type radiation was unstable and fluctuating in time. The $P(\omega_c) - I_d$ pattern recorded as I_d increased did not always agree with that as I_d decreased and also the radiated power in the latter case was several db larger than that in the former very often. The current range in which the N-type radiation occurred, however, did not alter when the $P(\omega_c) - I_d$ pattern was recorded successively at a constant pressure. These circumstances were considered to be due to the state of discharge plasma, a rough

estimation of which might be made from the discharge current I_d vs. the terminal voltage V_d . Therefore the $I_d - V_d$ characteristic at ω_c was measured at the same time with the $P(\omega_c) - I_d$ pattern. As shown in Fig.5b, there was a difference between the voltages V_d as I_d increased and as I_d decreased, but a quantitative relation between the $P(\omega_c) - I_d$ pattern and the $I_d - V_d$ curve could not be obtained.

Since the intensity of the N-type radiation can vary by several orders with I_d , the detailed variation of the intensity as a function of I_d is not obtained from the $P(\omega_c) - I_d$ pattern but obtained from $P(I_d) - B$ patterns. In Fig.6, the radiation power of N-type is plotted in db as a function of the current I_d , taking the noise power of the radiometer itself as unit. The thermal noise curve is replotted in db from the $P(B=0) - I_d$ pattern. In addition, $NS=3.8$ db shows the radiated power from the noise standard. It is seen from this figure, that $P(\omega_c)$ for Xe plasma becomes larger rapidly with the increasing I_d in the vicinity of $I_d \approx 400$ mA and reaches a saturation value above $I_d \approx 700$ mA, which is an enormously large value amounting to 25 db. It is also seen that, $P(\omega_c)$ for Kr plasma increases steeply at $I_d \approx 10$ mA and amounts to 31 db at about $I_d = 150$ mA and then falls down with the increasing I_d . In Ar plasma, the N-type radiation was observed in the pressure range of $p \approx 10^{-1} \sim 1$ mm Hg, although its intensity was not so large, as compared with that of Xe and Kr plasmas. In Ne and He plasmas the N-type radiation was not observed for any pressure.

The N-type radiation, of which the experimental data was described above, has the following characteristics.

- (i) The occurrence of this radiation is dependent on the kind of gas used. In our experiments, the N-type radiation was not observed in He and Ne plasmas, but observed in Ar, Kr and Xe plasmas.
- (ii) The N-type radiation occurs at the cyclotron field ω_c

independently of the current I_d , i.e., electron density or ω_p . This conclusion was obtained from the following experiment: the field intensity B_c where the intensity of the N-type radiation reached a maximum, was measured by a proton-meter. In Fig.7 is plotted the variation of B_c thus obtained, which was very accurate because of the sharpness of N-type peak, against I_d . It is known from this figure, that B_c is independent of I_d within the fluctuation of ± 0.12 percents:

$$B_c = 3,379 \pm 4 \text{ gaussess .}$$

On the other hand, the field intensity corresponding to the receiving frequency of our radiometer $\omega/2\pi = 9,485 \text{ Mc}$ is 3,387 gaussess, which is different from the experimental B_c by about 0.2 percents.

(iii) The intensities of the N-type radiation are enormously large and amount to 27 db in Kr and to 22 db in Xe above the respective blackbody radiations, as shown in Fig.6. In comparison with the power level (NS) radiated from the noise standard, whose radiation temperature was known to be about $1.1 \times 10^4 \text{ }^\circ\text{K}$, such large powers are shown to correspond to those radiated from the plasma in the thermal equilibrium equivalent to $5.5 \times 10^6 \text{ }^\circ\text{K}$ in the case of Kr and to $1.5 \times 10^6 \text{ }^\circ\text{K}$ of Xe.

(iv) N-type radiation is very sharp. Its width is by one order smaller than that of the normal cyclotron resonance and becomes broader with increasing gas pressure p . In Fig.8 is plotted the width (an approximate half width) of the N-type radiation, ΔB in gauss as a function of pressure p on Kr plasma, which was obtained from the $P(I_d) - B$ patterns. For reference, are shown also half widths of the normal cyclotron resonance which were measured on the positive column, only a part of which being placed in a magnetic field.

(v) The N-type radiation occurred only in the appropriate pressure range of $p = 1 \times 10^{-1} \sim 5 \text{ mm Hg}$ in our experiments. Above this range only the P-type radiation occurred and below it the peaks at cyclotron

harmonics were observed.

(vi) The N-type radiation was observed on the dc discharge plasma, when the whole tube was placed in a magnetic field, but not when only a part of the positive column was immersed in the field.

§ 4. Discussions

It will be considered here that by what mechanism can be explained the excitation of the N-type radiation of the characteristics mentioned above.

It was shown by Brown et al.¹⁵⁾ that, when the free electrons in plasma have a non-maxwellian velocity distribution, the radiation temperature T_r is not necessarily equal to the electron temperature defined by the average electron energy, that is, the relation $3kT_r/2\bar{u} = 1$ does not necessarily hold, where \bar{u} is the average energy of electrons. The ratio $3kT_r/2\bar{u}$ varies with the form of distribution function and the energy dependency of collision cross section for momentum transfer, but does not exceed 2.5. Therefore, an increase in radiation power due to a departure of the radiation temperature T_r from the electron temperature is 3 db at most. The radiated power of N-type obtained in this experiment, however, was more than 20 db above that of blackbody as shown in Fig.6.

It was reported by Smullin et al.¹⁹⁾ that when a pulsed, 10 KeV, 1 Amp electron beam was injected into a drift region, where a pressure of $10^{-4} \sim 10^{-3}$ mm Hg of Ar or H₂ was filled, the strong rf field was observed before the break of the collector current. The oscillation frequency of this field started at cyclotron frequency and increased steadily with time until the plasma frequency at the end of pulse. These results were interpreted that the initial cyclotron-frequency oscillation excited the plasma electrons and the plasma density increased, and the frequency of oscillation shifted to the plasma

frequency. If N-type radiation occurs from the same mechanism as that of Smullin et al., it will be expected that the N-type radiation must vanish instantaneously, because it excites plasma electrons and the plasma density grows up. On the contrary, the N-type radiation in our experiments had existed permanently. Moreover, such a assumption can hardly explain why the occurrence of the N-type radiation depends on the kind of gas and this radiation was not observed at the pressure $p \lesssim 10^{-1}$ mm Hg.

On the other hand, the possibility of the negative absorption, i.e., the amplification of radiation at radio frequency in its passage through the plasma has been first suggested by Twiss¹⁴⁾ for explaining the very intense radio noise emitted from some radio stars. Discussing this problem in detail, Brown et al.¹⁵⁾ stated that such an effect would also have important consequences on the total radiant energy loss from controlled thermonuclear devices. As suggested by Brown et al., the condition for a negative radiation temperature at the cyclotron resonance in a weakly ionized gas, will be obtained as follows.²⁰⁾

The radiation temperature T_r , generalized to an arbitrary distribution of electron energy $f(\epsilon)$, is

$$k T_r = - \frac{\int j_\omega(\epsilon) f(\epsilon) d\epsilon}{\int j_\omega(\epsilon) [\partial f(\epsilon) / \partial \epsilon] d\epsilon}, \quad (3)$$

where $j_\omega(\epsilon)$ is the emission rate of radiation by single electron of the energy ϵ at the radian frequency ω . When the emitting electrons of a plasma are sufficiently sparsely distributed that they radiate as if in vacuo, and their respective cyclotron motion is interrupted periodically by collisions of the frequency ν , the power radiated from single electron is²¹⁾

$$j_\omega(\nu) = \frac{e^2 \omega^2 \nu^2}{24 \pi^3 c^3 \epsilon_0} \left(\frac{1 + \cos^2 \theta}{2} \right) \frac{\nu}{\nu^2 + (\omega - \omega_b)^2}, \quad (4)$$

where v is a velocity of an electron and θ an angle between the direction of radiation and the magnetic field.

Now, it is assumed that all of the plasma electrons have the same energy $\epsilon = mv_0^2/2 = \bar{u}$ and their spatial distribution is isotropic, that is,

$$f(v) = (4\pi v_0^2)^{-1} \delta(v - v_0), \quad (5)$$

where δ is a delta-function. Further, the collision frequency is assumed to be:

$$\nu(v) = n_a v Q_m(v) = apv^{h-1}, \quad (6)$$

where $Q_m(v) \propto v^{h-1}$ is the collision cross section for momentum transfer, p the gas pressure and a, h constants, and n_a the number density of neutral particles.

Substituting Eqs. (4), (5) and (6) into Eq. (3), the radiation temperature is obtained:

$$3kT_r/2\bar{u} = Y(h, \omega), \quad (7)$$

where

$$Y(h, \omega) = \frac{3 \left\{ 1 + \left(\frac{\omega - \omega_p}{\nu_0} \right)^2 \right\}}{(3+h) \left\{ 1 + \left(\frac{\omega - \omega_p}{\nu_0} \right)^2 \right\} - 2h} \quad (8)$$

and $\nu_0 = \nu(v_0)$.

In the vicinity of the cyclotron field $|\omega - \omega_p| \ll \nu_0$,

T_r can be approximated by:

$$3kT_r/2\bar{u} = 3/(3-h). \quad (9)$$

Accordingly, T_r is negative for $h > 3$ and positive for $h < 3$.

By the same way, if the distribution function is assumed to be:

$f(v) \propto v^q \exp(-bv^2)$, b and q being constants, then the condition for

$T_r < 0$ is

$$q + 3 > h > 3. \quad (10)$$

Therefore, it is concluded that $T_r < 0$ can be satisfied if a departure of the distribution of plasma electrons from the Maxwellian is appropriate and the nature of gas used is $h > 3$. In the appropriate energy range, in which Ramsauer effect is large, the values of h for some rare gases can be approximated by that given in table 1. Out of rare gases, only Ar, Kr and Xe plasmas are expected to satisfy $T_r < 0$ in an appropriate electron energy range.

Table 1

Gas	energy range	h	$\frac{1}{2} \left(\frac{h-3}{h+3} \right)^{1/2}$	experimental value
Ar	1 ~ 10 eV	3.6	0.15	} about 0.1
Kr	1 ~ 7	4.24	0.20	
Xe	1 ~ 5.5	4.46	0.22	

On the other hand, the absorption coefficient α_ω is given by:

$$\alpha_\omega = - \frac{32\pi^4 c^2 n_e}{\omega^2} \int j_\omega(\epsilon) \frac{\partial f(\epsilon)}{\partial \epsilon} d\epsilon, \quad (11)$$

where n_e is the electron density. Substituting Eqs.(4), (5) and (6) into Eq.(11), α_ω is obtained:

$$\alpha_\omega = AL^{-1} X(h, \omega), \quad (12)$$

where L is a length traversed by the radiation in a plasma,

$$AL^{-1} = \omega_p^2 / (c \nu_0) \quad \text{and}$$

$$X(h, \omega) = \frac{(h+3) \left\{ 1 + \left(\frac{\omega - \omega_p}{\nu_0} \right)^2 \right\} - 2h}{3 \left\{ 1 + \left(\frac{\omega - \omega_p}{\nu_0} \right)^2 \right\}^2}. \quad (13)$$

At the cyclotron field $\omega = \omega_p$, α_ω is

$$\alpha_\omega L = \{ (3-h)/3 \} A, \quad (14)$$

and so α_ω is negative for $h > 3$. It is natural from Kirchhoff's law that the condition for $\alpha_\omega < 0$ agrees with that for $T_r < 0$. The absorption coefficient at $\omega = \omega_p$ as a function of h is plotted in Fig.9,

where the curve $(-\alpha_\omega L A^{-1})$ corresponds to $\alpha_\omega < 0$. The amplification factor due to $\alpha_\omega < 0$ becomes larger with increasing h . In Fig.10 is plotted the absorption coefficient against the magnetic field ω_p at the fixed frequency ω (or against frequency ω at the fixed magnetic field ω_p) for the various values of h . In a narrow magnetic field (or frequency) ranged near the cyclotron field (or frequency), α_ω becomes negative (the radiation is amplified) and outside this range the radiation attenuates, and its boundary is given by:

$$|\omega - \omega_p| = \{ (h-3)/(h+3) \}^{1/2} \nu_0. \quad (15)$$

The radiation intensity I_ω that escapes per unit solid angle from unit area of surface on a homogeneous plasma, in the absence of reflections at the plasma boundaries is given by:

$$I_\omega = B(\omega, T_r) \{ 1 - \exp(-\alpha_\omega L) \}, \quad (16)$$

where

$$B(\omega, T_r) = \frac{\omega^2}{8\pi^3 c^2} k T_r = B(\omega, T_\theta) Y(h, \omega), \quad (17)$$

with

$$B(\omega, T_\theta) = 2 \bar{u} \omega^2 / (24 \pi^3 c^2). \quad (18)$$

$B(\omega, T_\theta)$ is a blackbody intensity from the Maxwellian plasma having the average energy $\bar{u} = 3k T_\theta / 2$. Substituting Eqs. (12) and (17) into Eq.(16), the intensity I_ω normalized to the blackbody intensity $B(\omega, T_\theta)$, is given by

$$I_\omega / B(\omega, T_\theta) = Y(h, \omega) [1 - \exp\{-X(h, \omega) A\}] . \quad (19)$$

In Fig.11 is plotted the intensity I_ω at cyclotron field as a function of A for $h = 0$, where $T_r > 0$, and $h = 3.5$, where $T_r < 0$. It is known, from this figure that, with increasing A , that is, the electron density ω_p or the plasma length L , the radiation intensity I_ω reaches a saturation value for $h = 0$, whereas I_ω becomes larger continuously for $h = 3.5$. It is characteristic for $T_r < 0$ that I_ω increases

infinitely with increasing optical depth $a_\omega L$.

There might be some question on the applicability of the theory given above, in which the optically tenuous plasma was treated, to the present experimental results in which measurements were carried out on the dense plasma as well as on the tenuous one. If it is accepted the assumption, that the N-type radiation observed experimentally results from the effect of a negative temperature, the experimental results can be interpreted from the theory given above.

The characteristics of the N-type radiation which were summarized at the end of §3 are agreed with the theoretical results as follows: the N-type radiation occurs (i) in Xe, Kr and Ar plasmas alone and (ii) at the cyclotron field ω_c and (iii) its intensity is enormously large compared with that emitted from blackbody. Since the effect of a negative absorption occurs in a narrow magnetic field range given by Eq.(15), the ratio of half width of the N-type radiation to that of the cyclotron radiation is approximated to be $\{(h-3)/(h+3)\}^{1/2}/2$. This ratio, theoretical and experimental, for the gases under study is given in Table 1. The characteristic of the N-type radiation (iv), that its width becomes broader with increasing gas pressure, corresponds to the content given in Eq.(15).

As noted previously, it is necessary for $T_r < 0$, that the distribution function of plasma electrons is appropriate. It may be considered that this appropriate distribution was established in the dc discharge plasma, in the case when whole tube was placed in magnetic field, but was not in the plasma, in the case when only a part of positive column was immersed in the field, and therefore in the former case the N-type radiation was observed, but not in the latter case (characteristic of the N-type radiation (vi)). For our simple tube shown in Fig.1, such an appropriate distribution also might be established in the limited pressure range alone (characteristic of the

N-type radiation(ν)).

Furthermore, $P(\omega_c) - I_d$ patterns fluctuating in time were different according as I_d increased and decreased, as well as the $I_d - V_d$ curves for the dc discharge plasma used in measurements of the N-type radiation, as shown in Fig.5. These facts may be considered to be based upon the instability of the distribution function of plasma electrons.

The amplification factor ($-\alpha_\omega L A^{-1}$) is 4.5×10^{-1} for Kr and Xe and 1.7×10^{-1} for Ar respectively, as given in Fig. 9, therefore in Ar plasma the phenomenon of negative temperature is difficult to occur, compared with Kr and Xe. This situation was ascertained in our experiments. On the other hand, Ohara²²⁾ showed in his works that the voltage vs. current of Langmuir probe for Xe, Kr and Ar plasmas had a negative character, which was small for Ar plasma as compared with Kr and Xe. The circumstance of this may be analogous to that of the N-type radiation.

§ 5. Conclusion

The anomalous microwave radiation, named N-type radiation, from the plasma in magnetic field was observed. On this N-type radiation the following characteristics were found experimentally.

- (1) The N-type radiation was observed in Xe, Kr and Ar plasmas, but not in Ne and He plasmas.
- (2) It occurred at the cyclotron field independently of the discharge current.
- (3) Its intensity was extremely large compared with blackbody radiation and amounted to the power radiated from the plasma in thermal equilibrium equivalent to 5.5×10^6 °K in the case of Kr and 1.5×10^6 °K of Xe.
- (4) The width of it was smaller by one order than that of the normal

cyclotron radiation.

(5) It was observed in the pressure range of $p \approx 1 \times 10^{-1} \sim 5$ mm Hg.

(6) It was observed on a plasma when the whole tube was placed in magnetic field, but not when only a part of the positive column was immersed in the field.

On the other hand, it was shown that the cold plasma could have an effect of a negative radiation temperature at the cyclotron resonance, if a departure of the distribution function of plasma electrons from the Maxwellian is appropriate and the nature of gas used is $h > 3$ as given in Eq. (10).

Although the interpretation of the N-type radiation, observed in our experiments, remains to be somewhat questionable, if it is assumed that the effect of negative absorption is responsible for the N-type radiation, the experimental results obtained in this work could be interpreted from the theory of the negative radiation temperature given here.

The negative temperature phenomenon may be applicable to realize the maser, which might be called "plasma maser", its oscillation frequency being varied by the external magnetic field. In this case, the stimulated emission arises between the levels in the continuous energy range, while in the usual masers it arises between the discrete levels. If a microwave resonant system (cavity etc.), which was not used in our experiments, is used and its radiation energy is stored in this system as the usual maser does, then it may be expected that more intense radiation power of N-type than that of the present experiment can be drawn out from the magneto-plasma.

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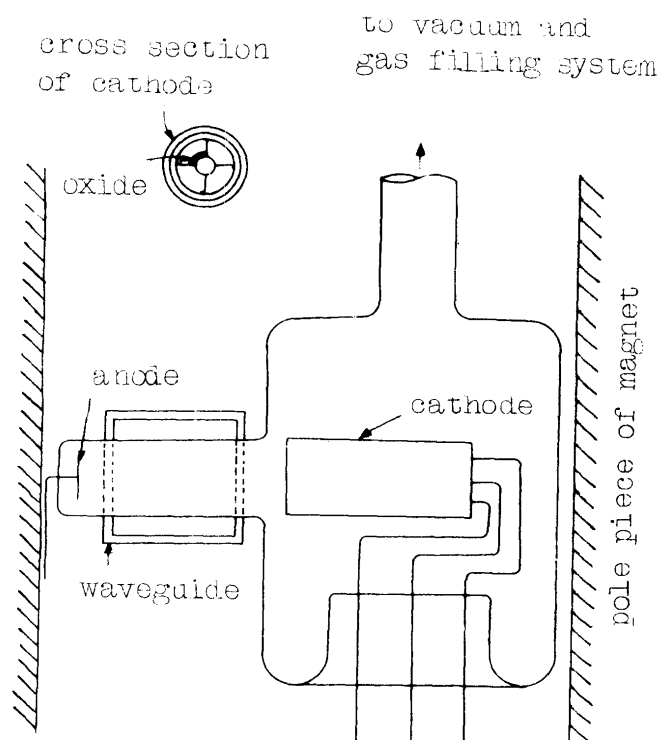


Fig. 1

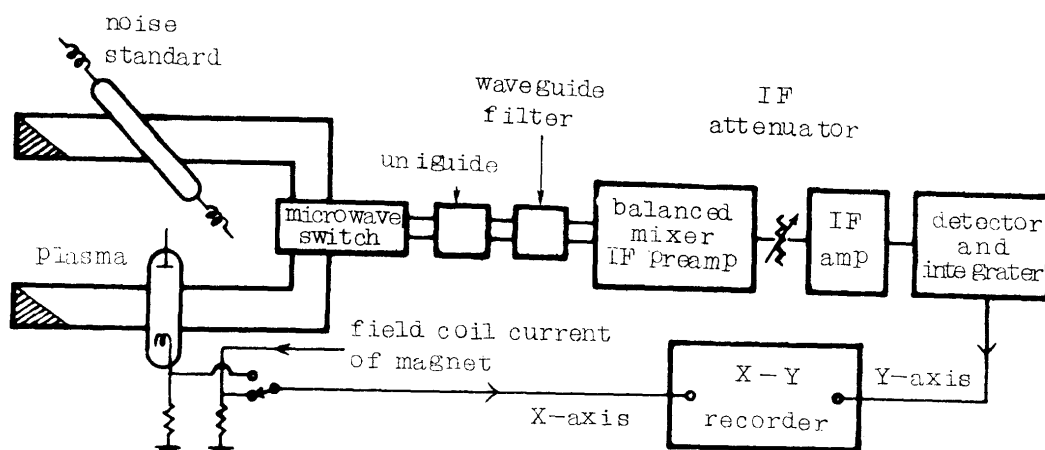


Fig. 2

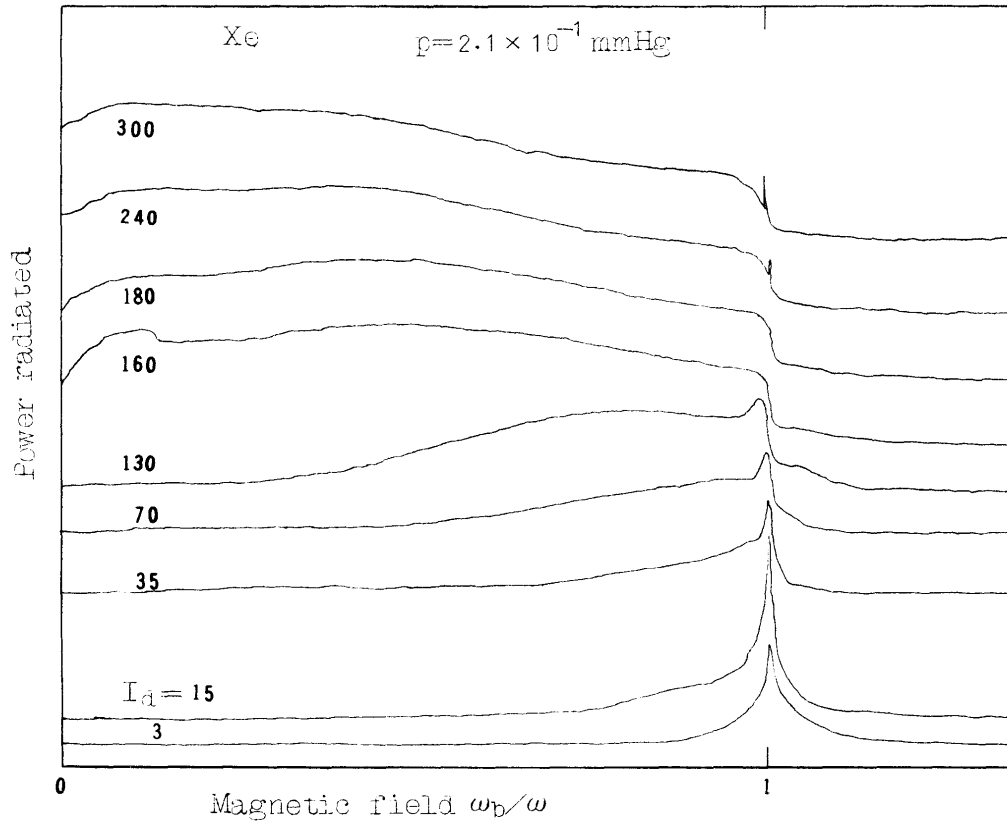


Fig.3a

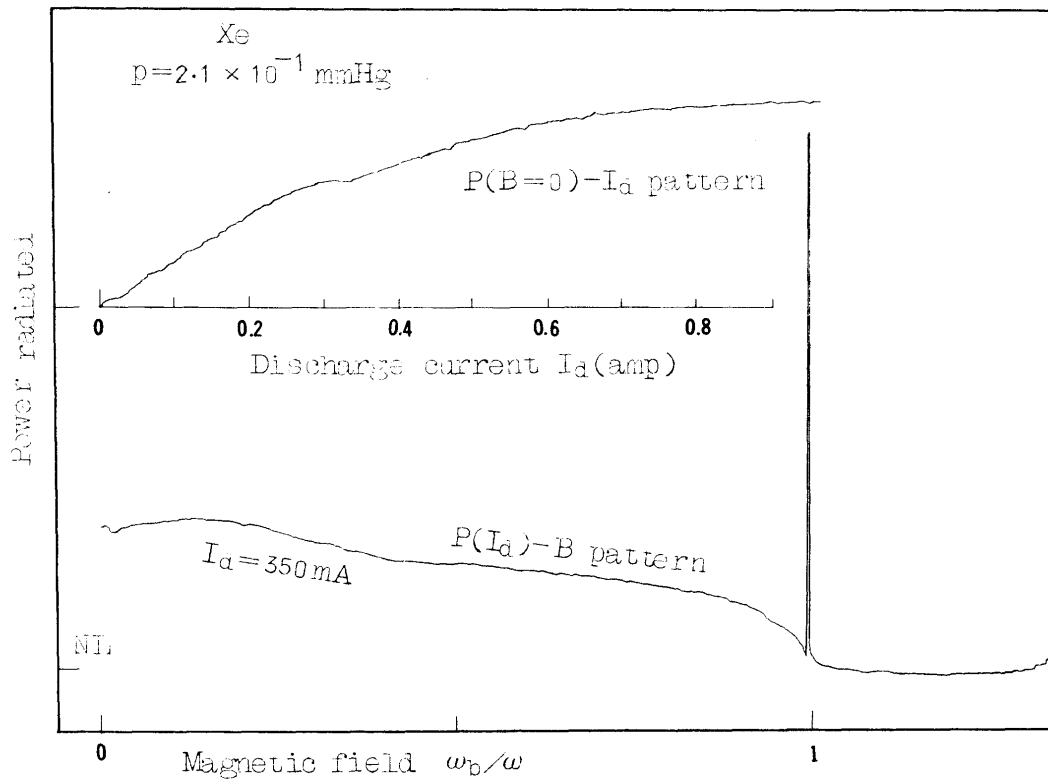


Fig.3b

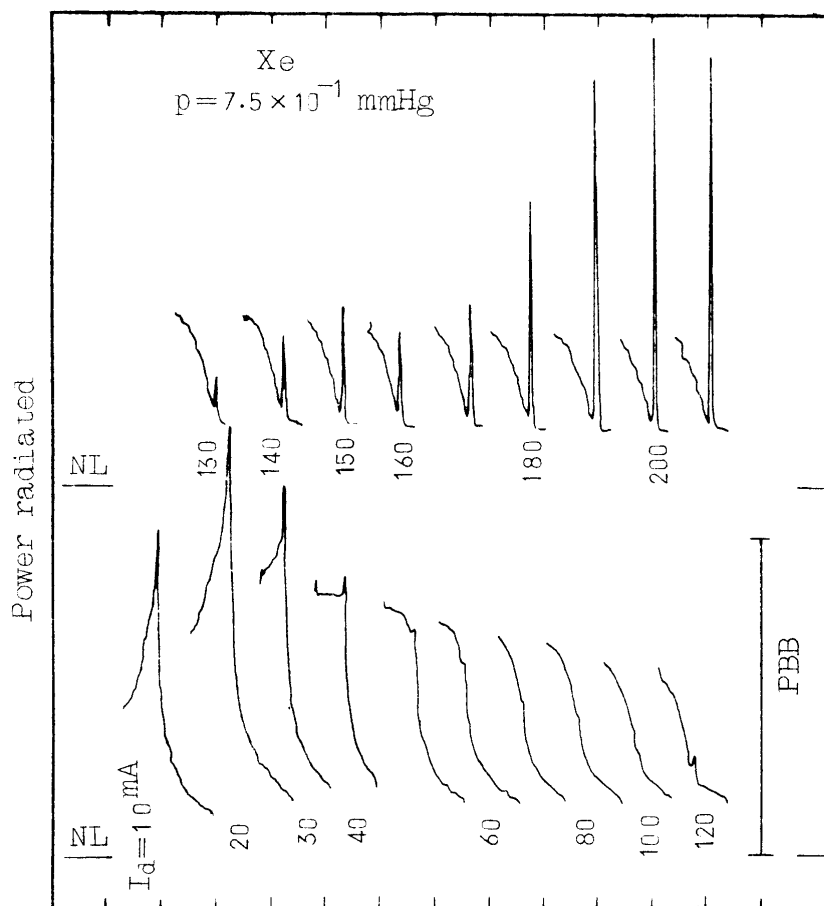


Fig. 4

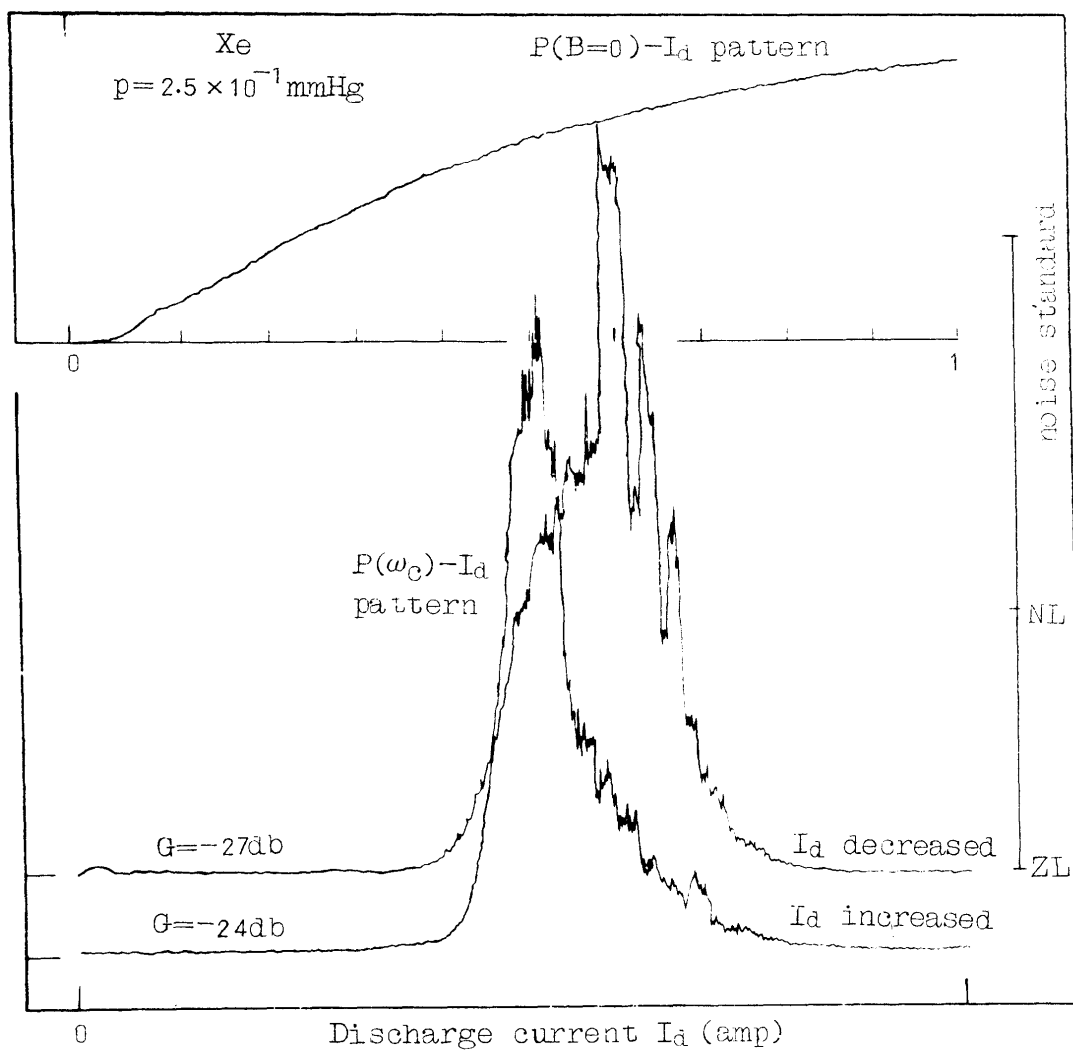


Fig.5a

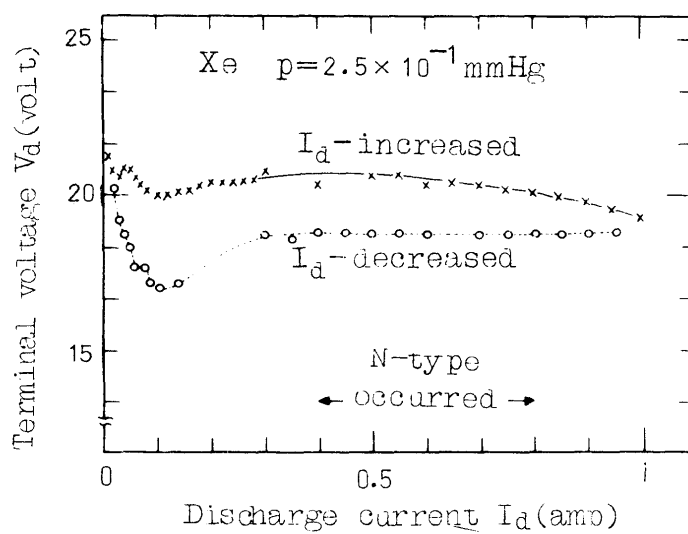


Fig.5b

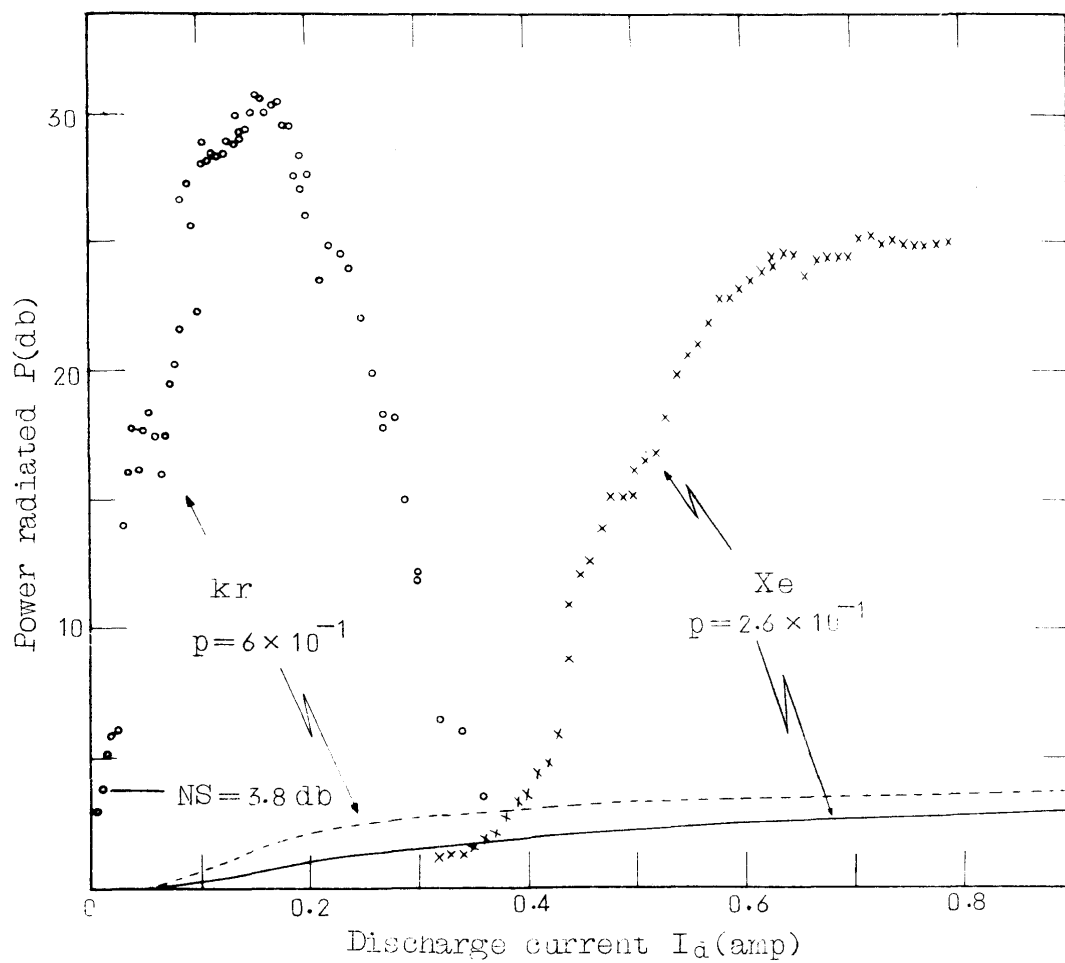


Fig. 6

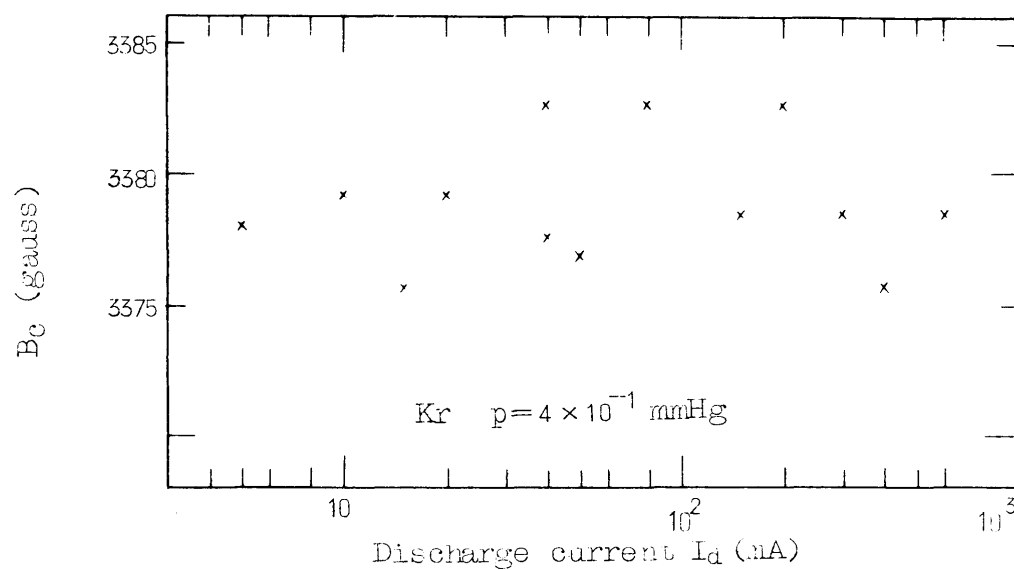


Fig. 7

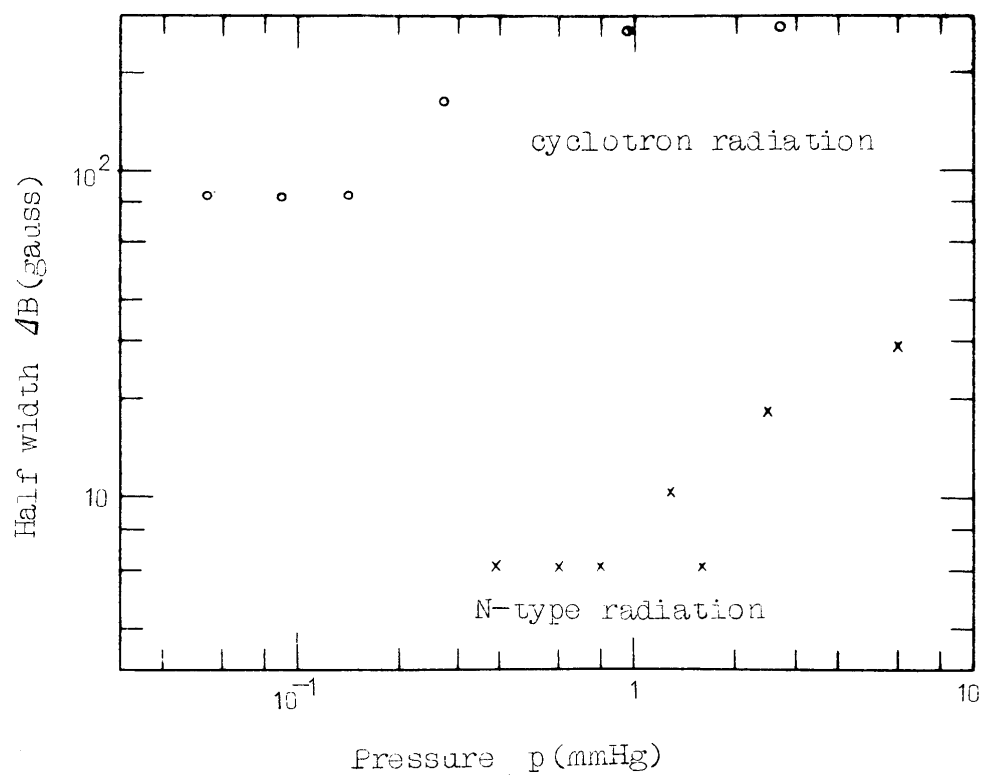


Fig. 8

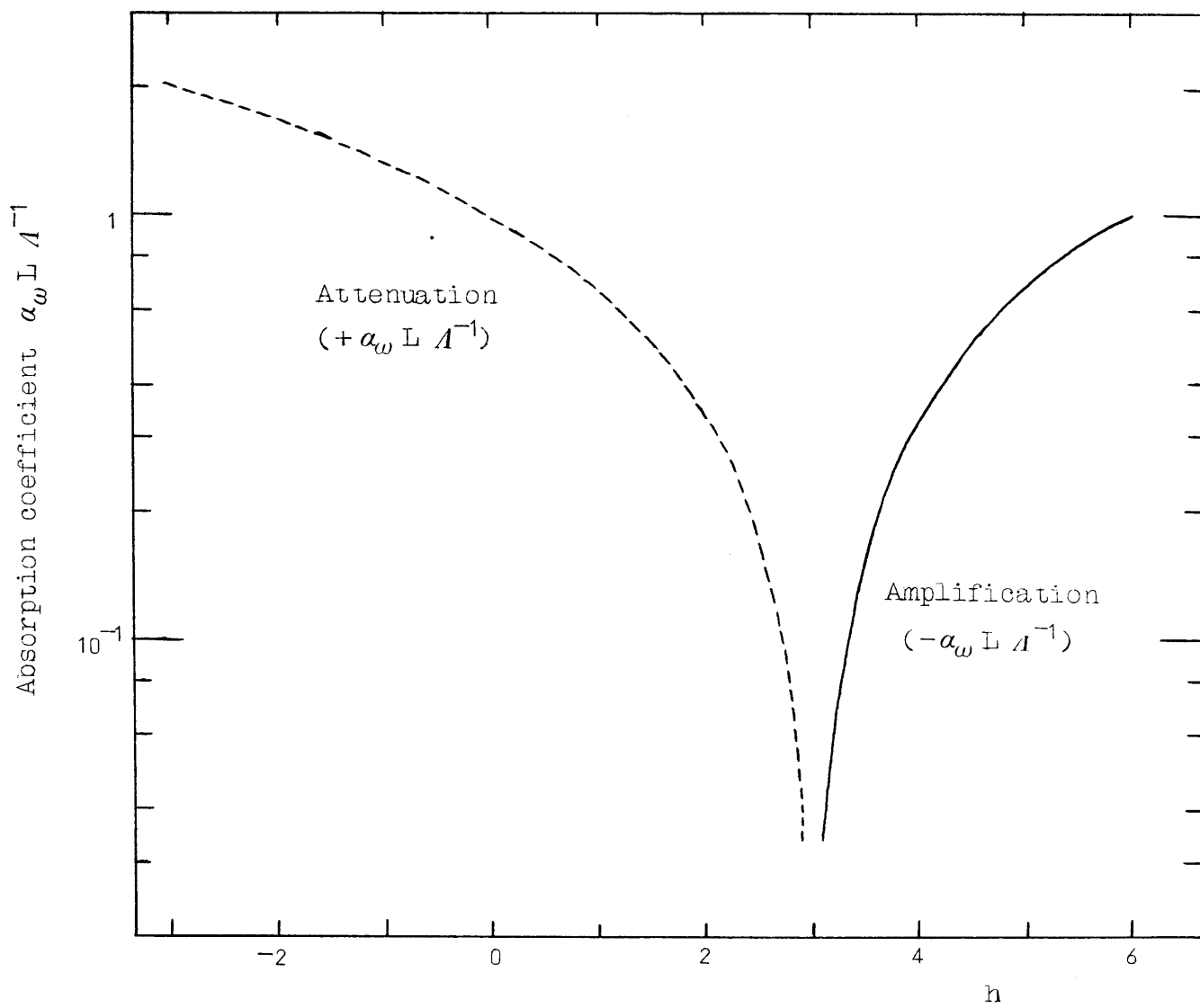


Fig. 9

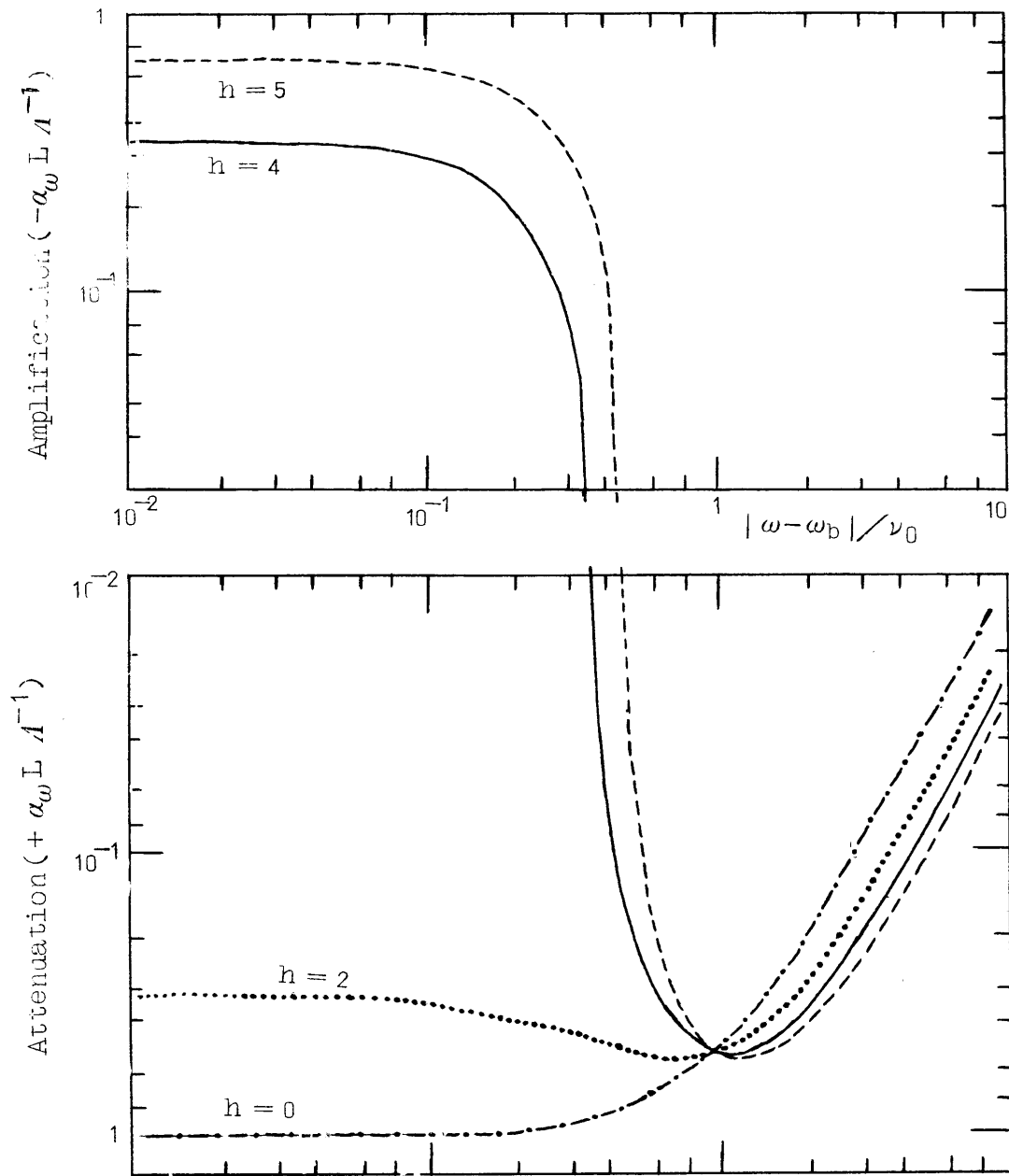


Fig.10

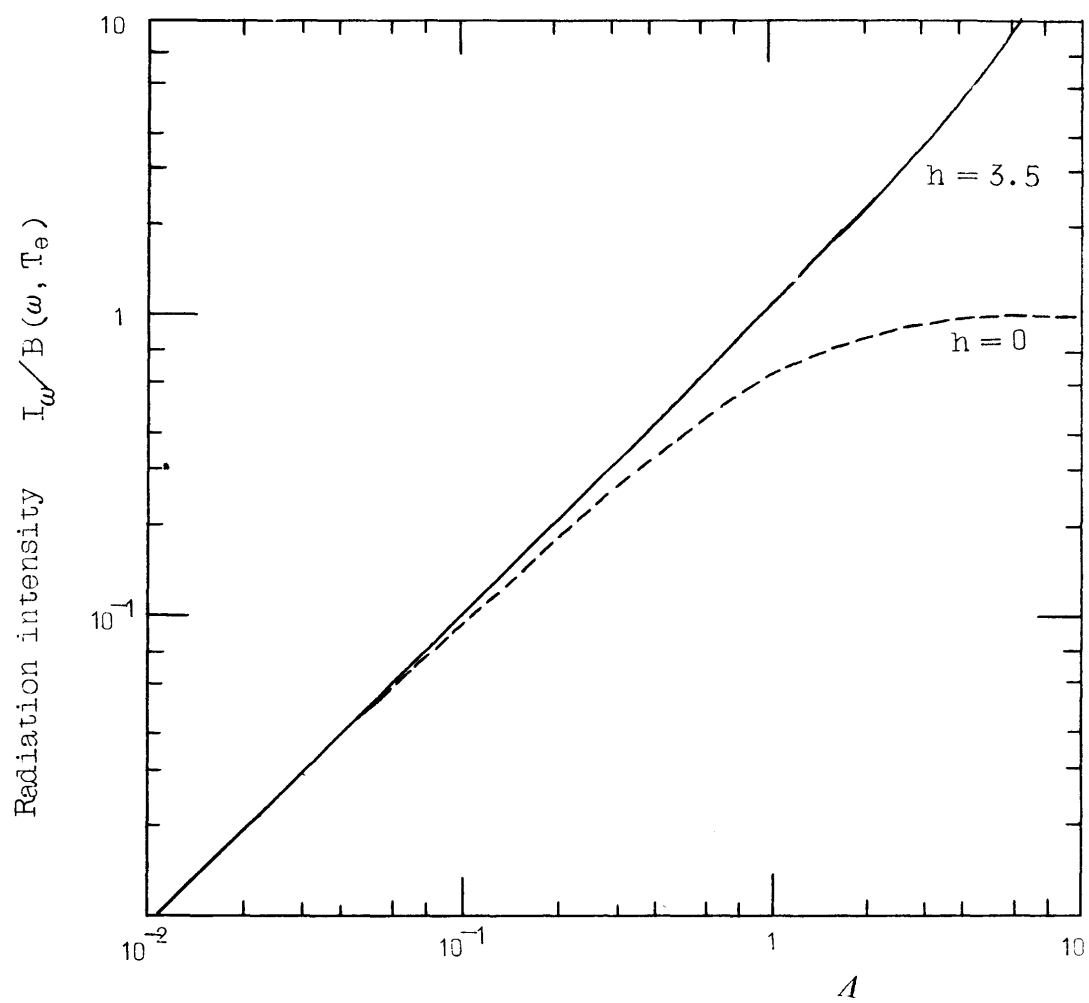


Fig. 11