EXPERIMENTS ON SELF-IONIZING SHOCK WAVES IN A MAGNETIC FIELD

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Abstract

The structure of a self-ionizing shock wave in He of 50 μ Hg has been studied experimentally. The shock wave was produced by means of an electric discharge and part of the shock tube was placed in a transverse magnetic field. By varying the strength of this magnetic field, it was possible to study the variation of the structure of the shock as well as the state of ionization behind the shock in the range of Mach number from 40 to 99.5 and of Magnetic Mach number (shock velocity/Alfvén velocity) 0.18 to 20. It was found that ionization behind the shock wave can be best explained in terms of streams of electrons and ions produced by the discharge.

Introduction

The characteristics of plasma produced by a shock wave have been the subject of extensive investigation in recent years, and a voluminous literature is available for the study of plasma in a state of local thermodynamic equilibrium (LTE)[1-4]. Also, a number of investigations have been reported on the mechanism of ionization behind shock waves[5-9]. However, most of these studies have been confined to an initial gas pressure in the range, say, of 1 mm Hg or higher.

The present experiment was designed to study the state of ionization behind the self-ionizing shock wave in low pressure. In particular, emphasis was placed on the study of the state of ionization in such a pressure range in the presence of a transverse magnetic field, so that the results could be utilized for future investigation of the micro-wave transmission (particularly, the whistler mode) through a plasma produced by the present apparatus under such circumstances.

Streak photography, time-resolved spectroscopy and magnetic probes were used as the diagnostic tools in the experiments. The results show qualitative agreement with the macroscopic theoretical description of the phenomena, in spite of the fact that it seems most appropriate to interpret the results in terms of streams of electrons and ions produced by the electric discharge, as the observations were made under non-LTE conditions.

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Experimental Arrangement

A general view of the experimental arrangement is shown in fig. 1. A Pyrex glass tube of 5.25 cm i.d. and 150 cm length was used as the shock tube, and at one end of this tube a coaxial electrical discharge system was placed. The discharge system consisted of a central electrode of stainless steel rod (0.64 cm o.d.) and an outer electrode made of a tapered aluminum cylinder (i.d. changing from 1.5 cm to 4.7 cm). A Teflon insulator was placed between these electrodes for spacing and this discharge system was directly connected to a 4,000 Joules (20 μf, 20 kV) condenser bank. A rotating mirror system was used to obtain a streak photograph, and the camera viewed the shock tube with a 45° mirror shown in fig. 1, since the electromagnet prevented a direct view of the shock tube from the side; the accuracy of time determination of this system was ± .05 μs.

A movable slit of width 2 mm was used for the light intake for the spectrograph. This slit moved inside of the system called "adjustable periscope" placed underneath the shock tube. With the use of photo-electric devices, time-resolved spectroscopic observations were obtained for He^{I}(5876Å), He^{II}(4686Å), and F^{II}(4246Å). F^{II} was selected because it should represent the propagation of the driving gas, since F^{II} can only originate from the ionization of the Teflon insulator.

A transverse magnetic field for the experiment was provided by an electromagnet of pole piece 30.5 cm in diameter, and a gap of 6.985 cm. The center of the pole piece was placed 65 cm from the coaxial discharge system, and at distances between 55 cm and 75 cm from the discharge system, a uniform field was obtained; this field decreased rapidly to 10% of the central value at about 28 cm from the center of the pole piece.

Two single turn coils 6 mm in diameter were used as the magnetic probes which were placed outside the shock tube with a separation of 9 cm. The signals of these probes were integrated electronically, and the time dependent variations of the magnetic field were recorded.

Typical records of experiments are shown in fig. 2, and consist of a streak photograph, and oscillograms representing time variations of line intensities of He^{I}, He^{II}, and F^{II}, and of the magnetic field which was measured at two different positions.

Experimental Results and Analysis

At distances of 20, 39, 51, 60, 69, and 79 from the coaxial discharge system (hereafter referred to as x in the text), records similar to those shown in fig. 2 were obtained, with the strength of the magnetic field equal to 0, 4, 8, 10 kilogauss*.

From the streak photographs and the beginning times of the line intensity signals of He^{I}, He^{II}, and F^{II} at various distances, the x-t diagram (speedgraph) shown in fig. 3 was constructed.

*Strength of magnetic field hereafter refers always to the initial strength of magnetic field at the center of the uniform region between the pole pieces.

**For convenience, the beginning of the He^{I} signal was assumed to represent the shock front.

It was found that the front appeared in the streak photograph closely corresponded to the loci of maximum line intensities of He^{I}, as well as He^{II} and F^{II}.

It can be seen in fig. 3 that (1) the magnetic field slows down the propagation of shock** strongly near the entrance of the pole pieces (x=50 cm), and that (2) the flow velocity behind the shock (defined by the luminous front in streak photographs, since it corresponded to the propagation of F^{II}), is roughly equal to the shock velocity. The latter characteristic suggests the possibility of incomplete shock formation under the experimental circumstances since the flow velocity must be slower than the shock (see Discussion section). To illustrate the strong effect of the interaction between the magnetic field and shock more clearly, fig. 4 was constructed from the magnetic probe data.

In fig. 4 the profiles of magnetic field, corresponding to various positions of the shock front, are shown, and it can be seen that the maximum variation of magnetic field (the strongest interaction between shock and magnetic field) occured near the entrance of the pole pieces (x=50 cm).

Similar results are tabulated in table 1 in terms of percentage changes of the magnetic field strength at various x for four different initial magnetic field strengths. These percentage changes were evaluated by using the values of maxima of the variation of the magnetic field.

Another summary of the experimental results is presented in fig. 5 in which the change of shock speed is shown in terms of the Magnetic Mach number $M_A^2 = 4\pi\rho U^2/B^2$, and the Mach number $M^2 = U^2/c^2$, where U is the shock velocity, c, ρ, and B represent the speed of sound, the density and the strength of initial magnetic field in the undisturbed gas, respectively. It can be seen in fig. 5 that the flow becomes subsonic (magnetically) upon entering the region of strong magnetic field and then tends to become supersonic after leaving such a region.

Figure 6 illustrates another aspect of the effect of magnetic field on the shock, in which oscillograms of the intensity profiles of He^{I} and He^{II} obtained at various distances are compared for the cases of no-magnetic field and 10 kilogauss.

The ratio of He^{II} to He^{I} intensity was also evaluated from these oscillograms, the results of this analysis are presented in fig. 7, in which the maximum value of this ratio is plotted against x for the cases of 0 and 10 kilogauss.

The results shown in fig. 7 are in agreement with those in fig. 3. The gradual decrease of the ratio of He^{II} to He^{I} with the distance x in the case of no magnetic field can be attributed to the decrease of shock strength with x. In the case of 10 kilogauss, the large rise of the ratio near x = 51 cm can be accounted for by the presence of a strong interaction between the shock and magnetic field, and the subsequent behavior of the ratio can be understood as the slow down and re-acceleration of the shock front.

However, if we attempt to interpret these results in terms of the published data of ionization equilibrium under LTE conditions[2], we find the temperature behind the shock is in the range of 2-3 eV. On the other hand, if we compute the probable temperature behind the shock, utilizing the macroscopic conservation relations[10] (assuming complete ionization of He behind the shock), we find that the temperature must be in the range of 20-30 eV. It is found from computations (see Discussion) that under the present experimental circumstances, the LTE conditions have never been established behind the shock, which can be expected a priori, from the low initial pressure of 50 μHg.

Discussion and Concluding Remarks

In the range of low Mach numbers and high initial pressures, it has been shown that the macroscopic conservation laws can be used to describe the state behind a shock produced by an electric discharge[1]. Also, in gaseous discharge it is known that a luminous front propagates in a gas with the velocity of the order of 10^9 cm/sec[11,12]. Fowler and his collaborators[11,12] recently have advanced a theory describing such phenomena in terms of an electron shock wave; they considered that the major mechanism producing the luminous front is the ionization and excitation by the electron shock wave which propagates without transferring momentum to ions and atoms (or molecules). Thus according to their hypothesis, the shock velocity is similar to that of ion velocity behind the shock.

In the present experiments it was found that the speed of shock was similar to that of ions behind the shock (for example, F^{II}). Since F^{II} comes from the Teflon insulator, it can only be identified as the contact discontinuity front in terms of hydrodynamic interpretations. Further, the fact that the beginning of the F^{II} signal was sometimes ahead of the He^{II} signal, leads us to conclude that the observed shocks were probably caused by a cloud of F ions and electrons (originating near the discharge region) streaming through the stationary He gas in the tube.

This picture of the formation of the shock in the present experiments enables us to explain most of the observed results. Firstly, the similar speed of propagation of He^{I}, He^{II} and F^{II} and He atoms can only be produced effectively by atomic (or ionic) collisions between F and He atoms. Also, the observed lower values of temperature behind the shock, in comparison to the macroscopic estimate, can be interpreted through this picture; the temperature rise behind the shock results from the conversion of the kinetic energy of flow into the thermal energy of the gases, if only a fraction of He atoms can be set into motion by the present shock through atom-atom collision (or atom-ion collision) between He and F, lower temperature would be the natural consequence.

To elaborate on such an interpretation, the logarithmic growth rates of the intensity of He^{I} and He^{II} (dlnI/dt, where I denotes line intensity of the spectrum) are plotted against x, as shown in fig. 8. In fig. 8 it can be seen that in the case without magnetic field, the general trends are a decrease of the rate of He^{II} and an increase of the rate for He^{I} with distance x, indicating decrease of temperature (shock strength) with distance. For 10 kilogauss these trends reverse between x = 50 and 60 cm, and remain reversed for greater distances. This result can be interpreted in terms of deformation of the electron cloud near the entrance region of the magnetic field creating a large electric field which might have persisted beyond such a region.

Non-LTE computations based on temperature waves of 10, 20, and 30 eV passing through helium gas have been obtained. The results indicate, for the density of these experiments ($5 \times 10^{15} cm^{-3}$), that thermodynamic equilibrium conditions do not exist during the times of observation (5 μsec). For LTE conditions to be established, the following times are found to be necessary; (1) for T = 10 eV, t = 100 μsec, (2) for T = 20 eV, t = [redacted]^{10} μsec, (3) for T = 30 eV, t = [redacted]^{3} μsec.

Acknowledgement

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Percentage Change of the Magnetic Field

Initial Field Strength (Kilogauss)	Distance x (cm)				
	39	51	60	69	79
2	.507	.449	.184	.179	
4	.586	.326	.116	.127	.102
8	.536	.166	.048	.039	.025
10	.546	.101	.031	.023	.012

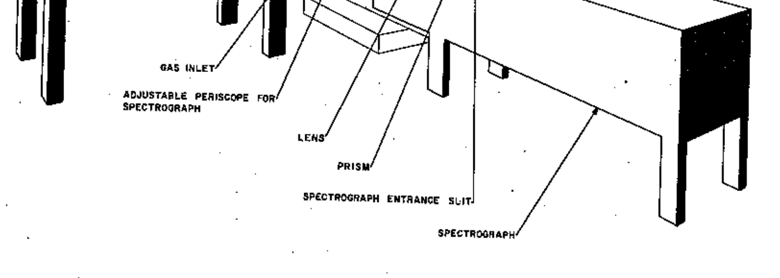

Figure 1. A general view of the experimental arrangement.

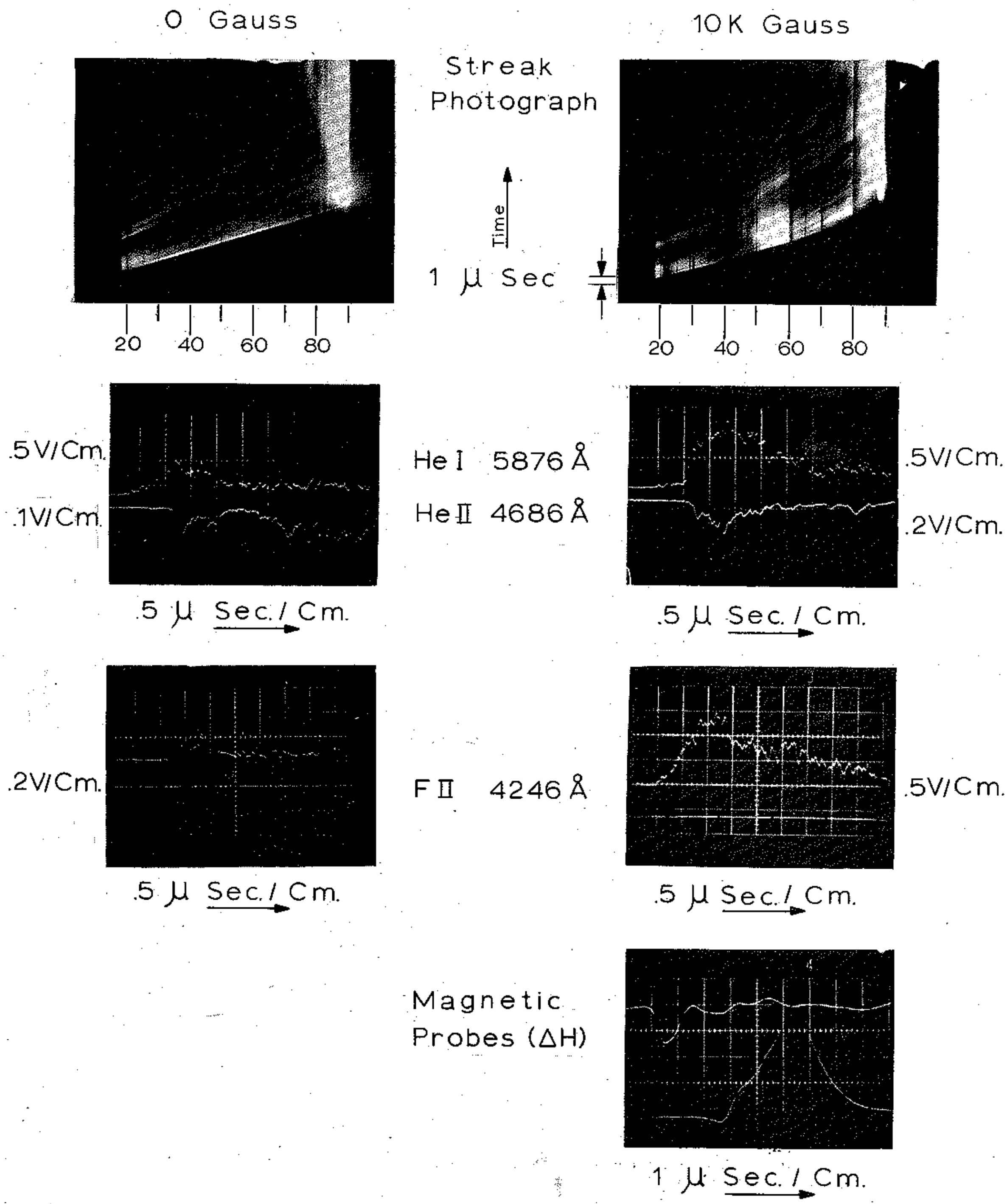

Figure 2. Typical records of experiments obtained at slit position 79 cm for 0 and 10 kilogauss of initial magnetic field.

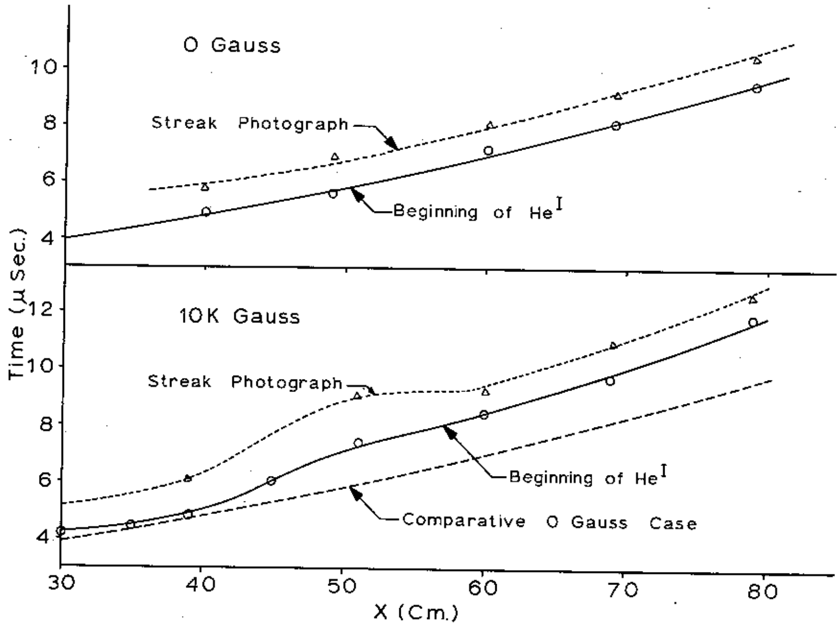

Figure 3. Speedgraph records obtained for 0 and 10 kilogauss of initial magnetic field.

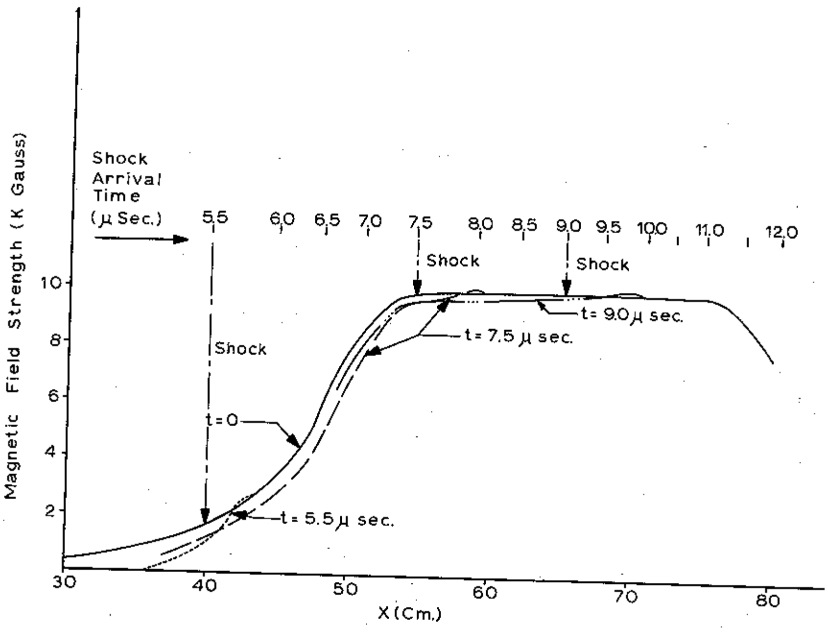

Figure 4. Magnetic field profile at various times (positions of the shock).

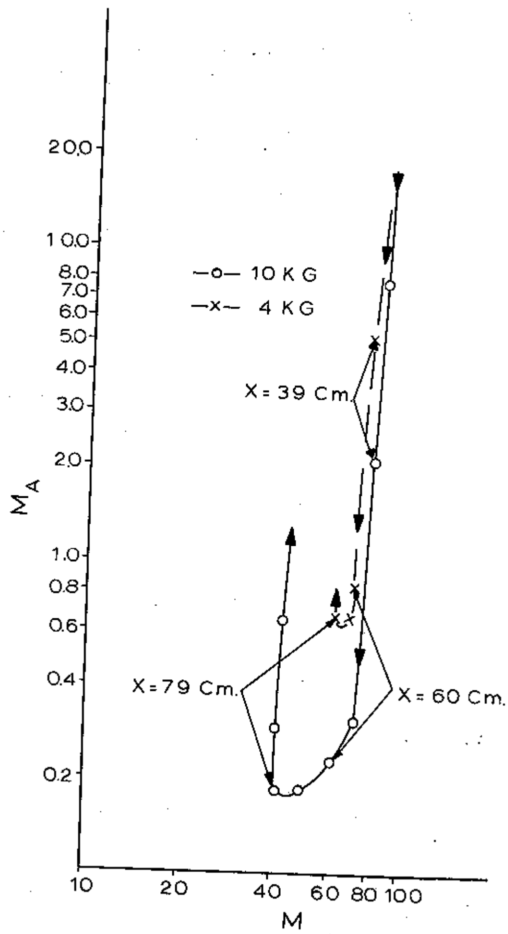

Figure 5. Summary of experimental results in terms of Magnetic Mach number M_A and Mach number M.

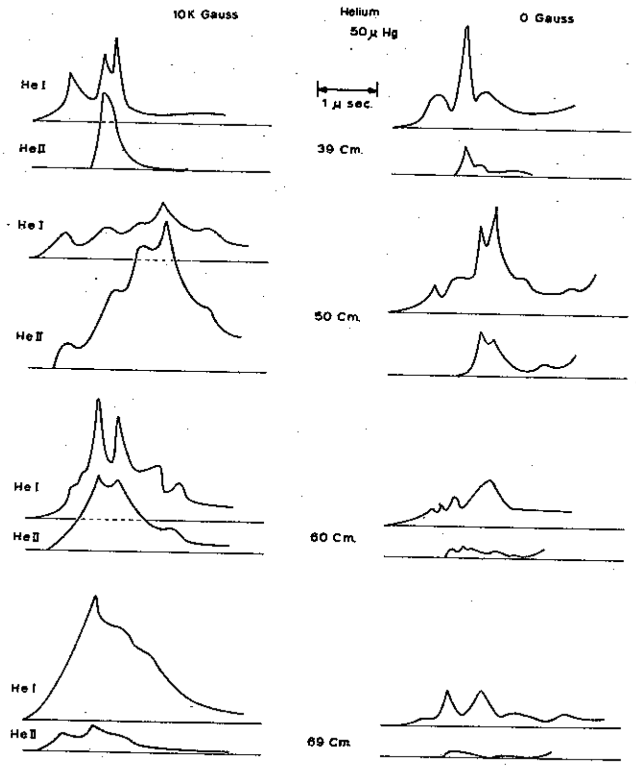

Figure 6. He^{I} and He^{II} line intensity profiles for 0 and 10 kilogauss of initial magnetic field at various distances.

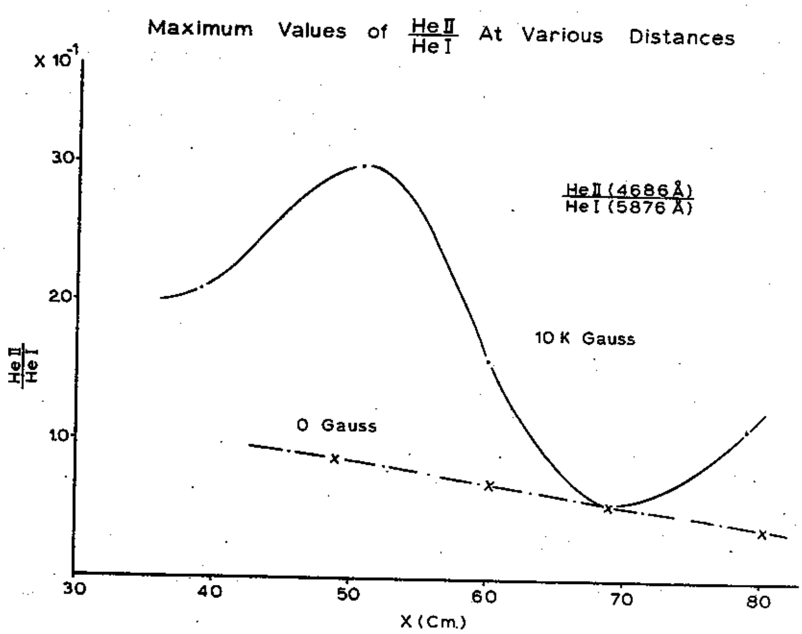

Figure 7. Maxium values of He^{II}/He^{I} intensity at various distances for 0 and 10 kilogauss of initial magnetic field.

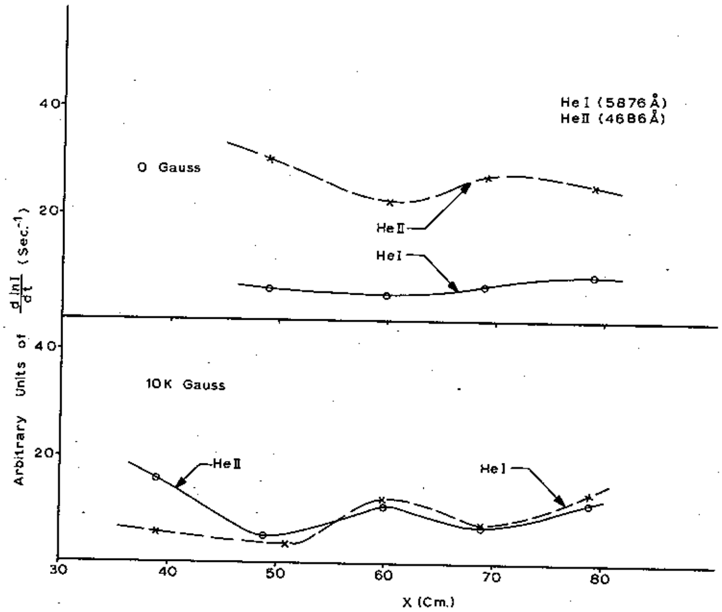

Figure 8. Logarithmic growth rates of line intensity of He^{I} and He^{II} at various distances for 0 and 10 kilogauss of initial magnetic field.

DISCUSSION

Question by E. SCHATZMAN (FRANCE) :

Have you similar experiments with other gases ?

Answer by Y. NAKAGAWA (U.S.A.) :

No, but we can performe a similar experiment with other gases quite easily.

Question by R.M. HOBSON (U.K.) :

Is the impurity detected by you in the shock heated gas as well as in the driven gas ?

Answer by Y. NAKAGAWA (U.S.A.) :

Unfortunately we had no means to check this, except the rate of leakage of vacuum was very low. But I believe the impurity is also in the driven gas.

Discussion remark by T.D. WILKERSON (U.S.A.) :

Many of the complications in this experiment may arise from an unfortunate geometry, whereby the induced current paths must close in sheaths and across magnetic lines.

Answer by Y. NAKAGAWA (U.S.A.) :

I agree 100 % with this comment and we are planning to do more clean cut experiment in this problem.