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Classical and Anomalous Diffusion of an Afterglow Plasma*

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The decay times of weakly ionized helium afterglow plasmas have been measured for neutral gas pressures between 0.2 and 0.8 Torr and magnetic field strengths from 0 to 800 G. Thus the transition from the field-free ambipolar diffusion to anomalous diffusion was covered. The plasma was confined by a cylindrical microwave cavity built in such a way that the end plates could be allowed to float electrostatically. With floating end plates we observed nearly classical diffusion, whereas anomalous diffusion was obtained when the end plates were kept at the same potential as the cylinder.

THE notion of anomalous or drain diffusion was introduced by Bohm *et al.*[1] in 1949 when they observed plasma losses from their calutron ion sources higher than expected from classical ambipolar diffusion. In 1955, Simon[2] suggested that it would be possible to explain the observed diffusion losses by classical diffusion theory, taking into account the effect of the conducting walls of the calutron ion sources. He calculated that the coefficient $D_\perp$ describing the transverse diffusion of a plasma should be approximately equal to $D_{i\perp}$, the transverse diffusion coefficient of the ions. However, experimental determination of $D_\perp$ by means of decaying plasma[3] showed that there is a substantial interval of magnetic field strength where $D_\perp$ is much bigger than the classical value but also much smaller than $D_{i\perp}$. Moreover, the experimental $D_\perp$ is proportional to $1/B$ and not to $1/B^2$ as suggested by Simon. In 1963 the problem of classical diffusion inside a conducting cylinder was treated independently by Golant[4] and by Whitehouse *et al.*[5] For the field strengths in question, their result is $D_\perp \approx 2D_{i\perp}$, obviously leading to bigger deviation from the experimental value than Simon's original result.

On the other hand, it has been found[3,6] that the diffusion rate is very close to the classical value if the plasma is confined by a glass cylinder, that is, by nonconducting walls. The nonapplicability of the available "short circuit" theories therefore leaves us with the question of how the conducting walls increase the diffusion rate unanswered. One result of the experiments described in this paper is that in a cylinder with conducting walls one obtains a diffusion rate near the classical value if the end plates are floating. The other result is that no critical field for the onset of anomalous diffusion was found when the end plates were at the same potential as the cylinder.

The apparatus is shown in Fig. 1. A microwave cavity was built in such a way that the end plates are separated a few tenths of a millimeter from the cylinder by means of quartz spacers. Wires leading to each of the end plates and to the cylinder are used to connect these parts electrically together or to leave them mutually isolated. We will refer to situations where these parts are connected or not as "connected" or "isolated" operation, respectively. The system was evacuated to about 3×10^{-9} Torr and filled with helium to a working pressure between 0.2 and 0.8 Torr. The helium was partially ionized by an electron beam shot into the cavity for about 1 msec. The decay of the plasma density following the ionizing pulse was observed by means of the frequency shift on the TM_{010} mode. As shown in Fig. 2, the plasma decayed exponentially with time. The decay was found to be fastest for connected operation and slowest for isolated operation. In the latter case the end caps assume a potential of about -0.4 V relative to the cylinder. Biasing the end caps with a potential relative to the cylinder between 0 and -0.4 V resulted in an intermediate decay time (see Fig. 2).

The slope of the logarithmic plots such as in Fig. 2 defines the decay times τ, which are related to the diffusion coefficients, $D_\perp$ transverse and $D_{\parallel}$ parallel to the magnetic field, by

$$1/\tau = (2.4/R)^2 D_\perp + (\pi/L)^2 D_{\parallel}, \qquad (1)$$

where R and L are the radius and length, respectively, of the cavity.

The presentation of the measured τ values as a function of magnetic field B and neutral gas pressure P is

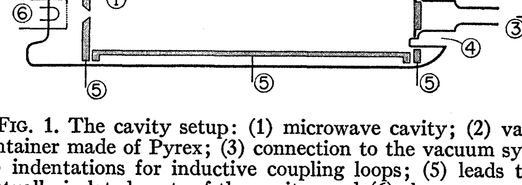

FIG. 1. The cavity setup: (1) microwave cavity; (2) vacuum container made of Pyrex; (3) connection to the vacuum system; (4) indentations for inductive coupling loops; (5) leads to the mutually isolated parts of the cavity; and (6) electron gun.

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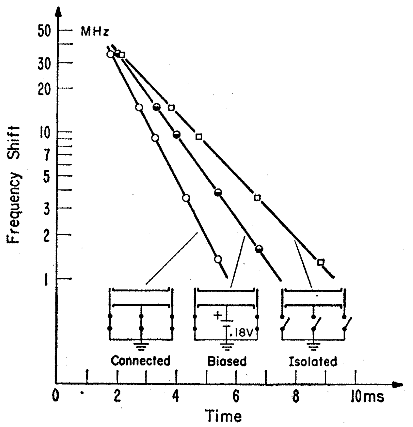

FIG. 2. The frequency shift as a function of time for different modes of operation. Data taken at $P=0.57$ Torr, $B=234$ G. A frequency shift of 1 MHz corresponds to an average plasma density of 7×10^7 cm^{-3}.

simplified by the fact that $P\times D_{\parallel}$ is a constant and that $P\times D_{\perp}$ is a function of P/B only in both classical and Bohm diffusion. Figure 3 shows $(R/2.4)^2P/\tau$ as a function of P/B. According to Eq. (1), the ordinates in Fig. 3 yield $P\times D_{\perp}$, plus a constant which accounts for the diffusion parallel to the magnetic field. The curve in Fig. 3 marked "classical" is calculated for an ion mobility[6,7] of 12.5 cm^2/V sec at STP and electron-neutral collision cross section of 5.3×10^{-16} cm^2. The experimental data represented by open symbols are obtained from measurements with isolated end caps and appear to be close to the classical value. The data obtained from connected operation, given by solid symbols, deviate considerably from the classical value. The transverse diffusion coefficient corresponding to these data appears to be not bigger than 3.8 times the Bohm coefficient.

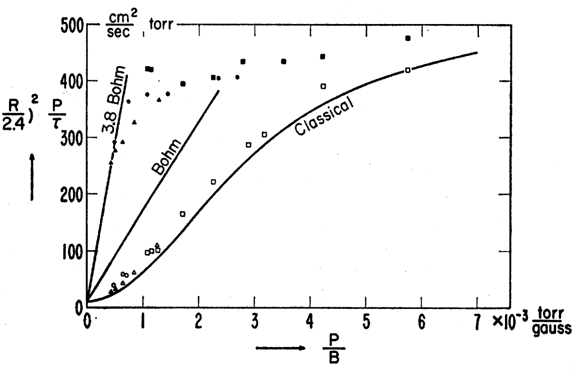

FIG. 3. The change of transverse diffusion with magnetic field. The open symbols refer to isolated operation; the solid symbols to connected operation; △, ▲ to 0.2 Torr; ○, ● to 0.3 Torr; □, ■ to 0.5 Torr.

In the experiment described here one can determine whether classical or anomalous diffusion will be obtained by turning a switch [between the leads (5) in Fig. 1]. According to the theory of decaying plasmas, we expect the density gradients and the temperature to be the same in either case. Thus the increased diffusion must be associated with the (diffusion-driven) current flowing through the plasma when end caps and cylinder are kept at the same potential. There is the possibility that this increase in diffusion is caused by a current-driven instability. However, within the accuracy of the measurements we found no critical field for the onset of such an instability. Increasing the magnetic field from zero to its maximum value (see Fig. 3) resulted in a continuous deviation of the diffusion rate from the classical value.

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