SOVIET PHYSICS JETP VOLUME 30, NUMBER 4 APRIL, 1970

INVESTIGATION OF THE "ANOMALOUSLY" ACCELERATED MOTION OF IONS IN A GAS UNDER THE ACTION OF AN ALTERNATING ELECTRIC FIELD

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Submitted March 14, 1969

Zh. Eksp. Teor. Fiz. 57, 1086–1089 (October, 1969)

Results are presented of an experimental investigation of the effect of a nonuniform alternating (sinusoidal) electric field on the motion of ions in a gas across a magnetic field. It is shown that the electric field has an "anomalously" strong effect on the duration of the motion of the ions. The existence of the phenomenon of "collision resonance" is established consisting of the fact that in the case of a definite relation between the frequency of collisions between ions and atoms and the frequency of the electric field the effect of the latter is maximized.

IT has been reliably established at present that the increased loss of charge from a plasma in a direction perpendicular to the magnetic field is due to the alternating electric fields brought about by different kinds of instabilities[1,2]. But the relationship between the anomalous diffusion and plasma oscillations usually remains at the level of a rough qualitative comparison. In this connection it appears to be of interest to carry out "model" experiments and, in particular, to investigate the motion of charges under the action of alternating fields in gases. An undoubted positive feature of such experiments is the possibility of complete direction and control over all the parameters characterizing the alternating field, and also the possibility of investigating the motion of the ions and of the electrons independently.

The object of the present paper is to study the effect of a spatially-inhomogeneous harmonic electric field on the motion of ions in a neutral gas of the same substance across a magnetic field.

The experimental method is based on the measurement of the time of motion of the ion from the axis towards the wall of a cylindrical chamber by the phase method[3]. A chamber of 42 cm length and 4 cm diameter was placed in a homogeneous magnetic field H of intensity up to 3100 Oe. In order to produce an electric field inside the chamber a thin (7.5×10^{-3} cm in diameter) metallic wire was placed along its axis and a high frequency voltage U was applied to it. The pressure of the working gas (helium) was within the range $1 \times 10^{-2} - 3 \times 10^{-1}$ mm of Hg. The gas was ionized along the axis of the cylinder by a narrow (of ~0.4 cm diameter) electron beam modulated harmonically at frequencies in the range 30–300 Hz. The energy of the electrons in the beam was 250 eV, the average current of the beam was 10^{-8}–10^{-7} A. The amplitude of the high frequency voltage U applied to the wire did not exceed in our experiments 2.5 V, and this definitely enabled us to neglect the effect of the electric field on the mobility of the ions[4]. The range of the working frequencies f was 10^5–10^7 Hz. The lower limit of the frequencies was determined by the condition $f \gg 1/\tau$, which enables one to investigate the "average" effect of the electric field. The upper limit of the frequency range was determined by the condition that the phase of the electric field strength should be the same over the whole volume of the experimental chamber.

By measuring the phase shift of the ion current to to the collector placed near the wall of the chamber with respect to the electron current which gives rise to the ionization of the gas one can determine τ-the time for the motion of the ions from the axis to the wall of the chamber. The quantity τ is determined both by the diffusion (with a velocity v_{diff}), and by the drift (with the velocity v_{dr}) motion of the ions. Since $\tau \gg \vartheta$ (where ϑ is the time between collisions of an ion with atoms), then we have

$$\tau = \int_0^R \frac{dr}{v_{\text{diff}} + v_{\text{dr}}} \qquad (1)$$

(here R is the radius of the chamber).

The degree of the effect of the alternating field on the motion of the ions can be conveniently characterized by the parameter $\alpha = \Delta\tau/\tau_0$, where $\Delta\tau = \tau_0 - \tau$. Here

$$\tau_0 = \int_0^R \frac{dr}{v_{\text{diff}}}$$

is the "diffusion" time for the motion of ions corresponding to the case when U, and consequently, also v_{dr} are both equal to zero. In the domain of small values of α the variation of α with varying U in fact represents the dependence of v_{dr} on the voltage on the wire.

Figure 1 shows a typical experimental dependence of α on the alternating voltage on the wire U; the figure also shows a similar dependence for the case when a constant voltage $U^=$ is applied to the wire which accelerates the ions from the axis towards the walls of the cylinder. We see that the nature of the dependence of α on the voltage on the wire in the cases indicated above turns out to be quite different: for a constant voltage this dependence is linear, while for an alternating voltage it is much closer to a quadratic one.

In Figs. 2 and 3 are shown experimental dependences of α on the generator frequency f for different magnetic fields H (Fig. 2) and pressures p (Fig. 3); a characteristic feature of them is the existence of the frequency region f_m for which $\alpha = \alpha_{\max}$, i.e., the time

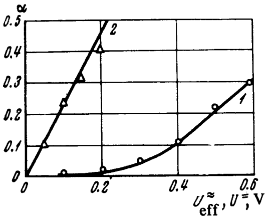

FIG. 1

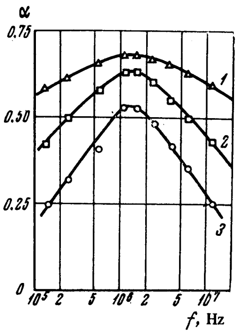

FIG. 2

FIG. 1. Dependence of α on the voltage applied to the axial wire for an alternating (1) and a constant (2) electric field. The conditions of the experiment are: $\rho = 6 \times 10^{-2}$mm of Hg, H = 650 Oe, f = 1.2 × 10^6 Hz.

FIG. 2. Dependence of α on the frequency of the electric field f for different magnetic fields: 1 – H = 650 Oe, 2 – H = 1700 Oe, 3 – H = 2700 Oe ($\rho = 9 \times 10^{-2}$mm Hg, $U_{eff} = 2$ V)

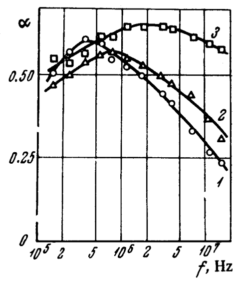

FIG. 3

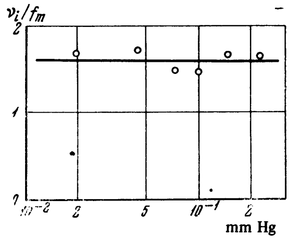

FIG. 4

FIG. 3. Dependence of α on the frequency of the electric field for different gas pressures: 1 – $\rho = 2 \times 10^{-2}$mm of Hg, 2 – $\rho = 5 \times 10^{-2}$mm of Hg; 3 – $\rho = 1 \times 10^{-1}$mm of Hg (H = 650 Oe, $U_{eff} = 2$ V).

FIG. 4. Dependence of the ratio ν_i/f_m on the gas pressure.

of motion is minimum. The quantity f_m is independent of the magnetic field (cf., Fig. 2) and grows with increasing pressure (cf. Fig. 3), so that β (the ratio of the average frequency ν_i of collisions between ions and atoms to the generator frequency f_m for which $\alpha = \alpha_{max}$) remains approximately constant, with β = 1.6–1.8 within the investigated range of frequencies and pressure (cf., Fig. 4). Thus, one can speak of the phenomenon of "collision resonance" which consists of the fact that for a definite ratio between the frequency of the electric field f and the collision frequency ν_i the time for the motion of the ions turns out to be a minimum.

The experimental results given above cannot be explained on the basis of such well-known mechanisms for the effect of an alternating field on the motion of charges as "heating"[5] and "high-frequency pressure" associated with the inhomogeneity of the electric field[6].

As is shown by simple calculations[7], for the whole range of experimental conditions the additional energy acquired by the ions during the time between collisions turns out to be much smaller than its thermal energy. Therefore, the variations of τ associated with an increase of the effective temperature and consequently, of the diffusion coefficient, turn out to be approximately by an order of magnitude smaller than those which are observed experimentally.

The effect of the "high-frequency pressure" in the absence of a magnetic field and without taking collisions into account can be easily estimated by determining the drift velocity of the ions under the action of the "high-frequency potential"[6]:

$$v_{HF} = b\frac{d\bar{\varphi}}{dr}, \qquad (2)$$

where b is the mobility of the ions $\bar{\varphi} = aU^2/\omega^2 r^2$ (here a is a constant, $\omega = 2\pi f$), and then, in accordance with (1) one can calculate τ, and consequently, also α. The maximum values of α for $U_{eff} = 1.5$ V amount to ~0.01, and this is considerably lower than the experimentally observed values $\alpha_{exp} = 0.5$–0.7 under the same conditions. Moreover, as can be seen from expression (2), as the frequency increases a monotonic falling off of α should occur, while experiment indicates the existence of a maximum at f_m. The reason for such a large discrepancy between calculation and experiment cannot be associated with the fact that the calculation was carried out without taking into account the "magnetization" of the ions. Indeed, as can be seen from Figs. 2 and 3, as ω_H/ν_i is diminished (here ω_H is the cyclotron frequency of the ions) α_{max} does not fall off, but even increases somewhat; moreover, the quantity ω_H/ν_i itself in our experiments in a number of cases amounted to only 0.25–0.50. Taking into account collisions between ions and atoms by means of introducing a force of friction leads only to a decrease in vhf since in this case the quantity $\bar{\varphi}$ is decreased by a factor of $(\omega^2 + \nu_i^2)/\omega^2$. On the other hand, the phenomenon of "collision resonance" itself indicates that collisions between ions and atoms of a gas play an essential role.

From what has been stated above it follows that in order to explain the experimental results given above (the "anomalously" strong effect of an alternating electric field, the phenomenon of "collision resonance") a special theoretical investigation is required.

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Translated by G. Volkoff