Acceleration of aluminum ions in a plasma focus

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An investigation of the mass composition of an ion bunch accelerated toward the cathode in a plasma focus of a deuterium discharge has shown that the deuteron bunch is accompanied by a beam of multiply charged aluminum ions if the compressed pinch was in contact with this metal. Acceleration of the ions Al^{V-IX} was observed in a mixture of D_2 and Xe with the MG installation in an "electrode" regime.

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We have used in the present study the known isolated-collector method, which makes it possible to investigate deuteron beams of energy insufficient to excite nuclear reactions,[1] as well as beams of other ions. We present below the results of measurements on aluminum ions produced from a metallic core at the center of a recess in the anode. The experiments were performed with the MG installation[2] with a discharge chamber equipped with a metallic liner of 1000 mm diameter and with a copper electrode of 700 mm diameter.

A bank of IMZ-50 capacitors amounting to 576 μF, at a voltage 16–18 kV, was discharged in the chamber through a vacuum discharge gap. The chamber was filled with a mixture of 0.6 Torr of D_2 and 20 mTorr of Xe; with a properly chosen external inductance, this led to an "electrode" discharge regime.

On the cover of the chamber (1) (see Fig. 1) was mounted a drift tube approximately 3.5 m long, evacuated to a residual pressure 3×10^{-5} Torr with a vapor-jet pump with nitrogen trap. An electromechanical valve (2) installed at the entrance to the tube made it possible to uncover an opening of 16 mm diameter for a time ~1.5 msec and initiate, when completely open, the discharge of the capacitor bank. The ion receiver was a graphite collector (3) of 100 mm diameter loaded through a 0.25-μF decoupling capacitor by the 91-Ω input of the S1-26 oscilloscope. The decoupling capacitor made it possible to apply to the collector a specified potential (in our case +140 V) and to determine the conductivity of the gap between the collector and the tube body, which was connected parallel to the load. The graphite collector served simultaneously as a carbon target in which neutrons were generated by the fast deuterons of the bunch.

A decrease of the plasma conductivity in the gap between the collector and the chamber, produced mainly by the operating speed of the valve, i.e., by the low plasma density, was additionally produced by insulating the collector electrically and magnetically. The collector disk was screened by a glass vessel (4) and placed in the magnetic field ~0.2 kOe of two coils (5) which were connected ahead of the discharge. The neutrons from the reaction $^{12}C(d,n)^{13}N$ were registered with the aid of a photoscintillation detector (7), and the induced activity was measured with an STS-5 β counter (16).

Figure 2a shows a typical oscillogram of the signal from the collector under a voltage +140 V in the case when the drift tube is filled with the gas mixture of the chamber (with the valve completely open). Starting with the instant of pinching of the discharge, the conductivity in the circuit between the collector and the tube body increases sharply because of the ionization of the gas that fills the gap. The load is practically completely short circuited, and the signal due to the ion current of the deuterons that strike the collector is manifest only by a small distortion of the smooth growth of the conductivity (indicated by the arrow on Fig. 2a). The combination of a vacuum shutter, a magnetic shield, and screening made it possible to increase substantially the resistance of the gap, from several ohms to several hundred ohms, and to photograph the ion current to the collector (Figs. 2b and 2c). Since the collector current can be the sum of the currents of different ions, we used magnetic separation. To this end a magnetic field of the order of 0.2 kOe was produced over a length 0.6 m in a narrow section of the drift tube, of 100 mm diameter, with the aid of two coils (8). This field prevented deuterons with energy less than 1.5–1.7 MeV from striking the collector (Fig. 2d). The deuterons with higher energy reached the collector (indicated by the arrow).

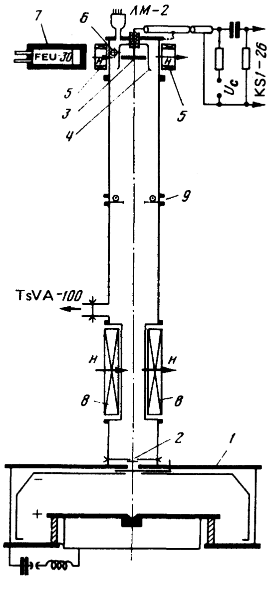

FIG. 1. Experimental setup and arrangement of the measurement apparatus.

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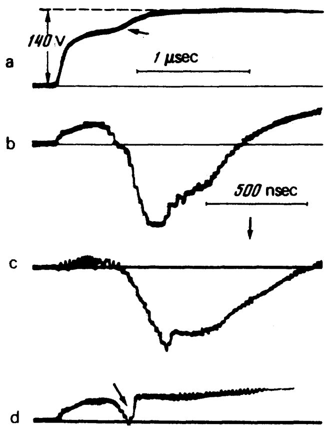

FIG. 2. Oscillograms of signals from the collector: a—with constantly open valve, b, c—with the pulsed valve operating but without a diagnostic magnetic field (8), d—with the pulse valve operating and the diagnostic magnetic field (8) turned on.

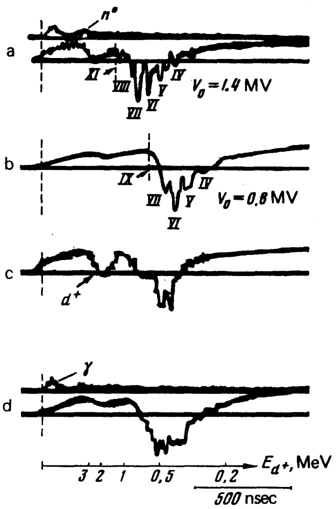

FIG. 3. Oscillograms of signals from the collector when aluminum is introduced into the focal zone.

In the experiments with the field, the deflection of the deuterons was monitored against the change of the distribution of the induced activity (the reaction $^{27}Al(d,p)^{28}Al$) in aluminum-covered β counters located in the upper part of the drift tube (9) on the sides of a 100×100 mm square.

The oscillograms of the current to the collector produced when the aluminum entered the focal zone are shown in Fig. 3. The collector-current oscillograms show a group of discrete peaks corresponding to the currents of ion groups of neighboring ionization multiplicity. From the ratio of the velocities of these groups we can determine the number of lost electrons and the accelerating potential. The time of flight was reckoned from the position of the γ pulse of the bremsstrahlung from the anode (assuming simultaneous acceleration of the ions and electrons), shifted by the time of flight of the γ quanta over the distance from the anode to the collector (12 nsec) and the delay time of the FÉU-30 photomultiplier (40 nsec). The ratios of the times of flight of the ions over the distance from the focus to the collector are

$$\frac{t_n}{t_{n+1}}=\left(\frac{n+1}{n}\right)^{1/2},$$

where $I \leq n \leq XII$ is the ionization multiplicity.

The values of n determined by this method for aluminum are marked on the oscillograms. For any of the peaks we can determine the accelerating potential by assuming $V_d = V_{Al}(13.5/n)^{1/2}$. The values of the ionization multiplicities determined from the velocity scale are indicated on the oscillograms. These regular groups of discrete peaks show that in these cases the ions are accelerated in one region that is strictly bounded in time and in space. The irregularity of the peaks on some oscillograms (Figs. 3c and 3d) can be attributed to interference of several parallel acceleration regimes having different accelerating potentials or different times at which such a region occurs. On the oscillograms of Fig. 3 (most clearly on 3c) one can note that the aluminum ion current begins to flow immediately after the vanishing of the deuteron current as a result of deflection in the magnetic field. Such large velocities can be possessed by the ions with maximum ionization multiplicity (XI–XIII). At accelerating potentials 0.7–1 MeV, however, the aluminum ions with such multiplicity, whose trajectories in the magnetic fields differ little from those of the deuterons, also are deflected away from the collector.

The number of ions striking the collector can be determined from the amplitude and time of the signal, taking into account the ionization multiplicity. Thus, for Al^{VII} (n = VI) (Fig. 3b), at a maximum current ~2.3A, about ~7×10^{10} ions reached the collector. The currents of ions with other multiplicities are also close to this value.

The signal (n^0) on the oscillogram of Fig. 3a corresponds to registration of the principal neutron pulse from the reaction $d(dn)He^3$ in the plasma focus and is connected with the insufficient shielding of the photomultiplier.

In conclusion, it must be noted that the presented oscillograms show no distinct signs of ions of the copper of which the electrode is made, although at the same ionization multiplicity the velocity of copper ions, for the same accelerating potential, is only smaller by a factor 1.5 than that of aluminum ions. It is probable that the copper vapor does not manage to reach the acceleration zone because of the lower rate of their propagation.

The development of the described method of analysis of ionic components at a corresponding choice of elements and method of their introduction in the focal zone can help to determine the most important parameters of the cumulation zone, such as $n\tau$ and T, and also the geometry of the fields of the acceleration zone.

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[1] N. V. Filippov and T. I. Filippova, Pis'ma Zh. Eksp. Teor. Fiz. **25**, 262 (1977) [JETP Lett. **25**, 241 (1977)].
[2] V. I. Agafonov, I. F. Beljaeva, V. F. Djachenko, *et al.*, Plasma Phys. and Contr. Nuclear Fusion Research-IAEA **2**, 21 (1969).

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Theory of thermomagnetic phenomena in the intermediate-pressure range

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A kinetic theory of thermomagnetic phenomena occurring in polyatomic gases (the effect of fields on transport phenomena) in the pressure range where the mean free path, $\bar{l}$, of the molecules is comparable to the geometric dimension, L, is proposed. An integral kinetic equation for a gas with rotational degrees of freedom in a magnetic field is derived which takes into account both intermolecular collisions and nonspherical collisions of the molecules with the walls. The distribution function for such a gas confined between two surfaces in a magnetic field is found for pressures at which $\bar{l} \lesssim 0.1L$. The contribution of the various collision processes to the observable changes that occur in the macrofluxes in the field is investigated. The effect involving the appearance in a magnetic field of a pressure difference in a closed plane channel whose walls have different temperatures is considered in detail.

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1. INTRODUCTION

A wide class of phenomena connected with the effect of external fields on transport processes are known at present to occur in rarefied gases.[1] They are due to the precession of the molecules in the field and the nonspherical nature of the collisions between the gas molecules and between the molecules and the walls. These effects are as yet clearly understood only in the limiting cases $\bar{l} \ll L$ and $\bar{l} \gg L$ (l is the mean free path of the molecules, L is the characteristic dimension). The first limiting regime is characterized by the Senftleben-Beenakker effect,[1,2] which is connected with a change in the thermal conductivity and the viscosity of the gas in the field. A thermomagnetic effect whereby a magnetic field affects the heat flux between two surfaces is known to occur in a Knudsen gas ($\bar{l} \gg L$).[3,4] In the limiting cases of high and low gas pressures the kinetic phenomena are wholly determined respectively by the nature of the collisions between the molecules and the walls.

In the intermediate-pressure regime, when $\bar{l} \sim L$, the transport phenomena are determined by both the intermolecular collisions in the gas and the interaction of the molecules with the surface of the solid. As a result, there are observed more complex dependences of the macroscopic fluxes in the gas (e.g., the heat flux) on the field. Furthermore, there occur in the intermediate-pressure range specific effects that disappear at high pressures ($l/L \to 0$). To such phenomena pertain the recently discovered effect involving the appearance in a field of a thermomagnetic pressure difference in a closed plane channel whose walls have different temperatures,[5] the effect of the thermomagnetic force acting in the field on a body in an inhomogeneously heated gas,[6] and the Scott effect,[7,1] which consists in the rotation in a field of a heated cylinder located in a polyatomic gas.

There virtually does not exist at present a kinetic theory that describes the thermomagnetic phenomena occurring in the intermediate pressure region. Attempts made earlier to describe the thermomagnetic-pressure-difference,[8] the thermomagnetic-force,[9] and the Scott[10] effects only allowed a qualitative explanation of these phenomena. In essence, only Vestner's approach,[8] which is based on the solution of the equations for the moments of the distribution function with phenomenological boundary conditions (at the walls) introduced by the method of nonequilibrium thermodynamics, constitutes an attempt at the construction of a consistent theory for the intermediate-pressure region. However, in such an approach the choice of the moments connected with the rotational degrees of freedom is not validated. Furthermore, such a theory, which is more of a hydrodynamic theory than a kinetic one, does not allow us to determine the contribution to the effects of the various collision processes (the intermolecular collisions or the collisions of the molecules with the surface).

In the present paper we construct for the thermomagnetic effects occurring in the intermediate-pressure range a consistent theory based on the use of the integral kinetic equation. The constructed theory can be extended to the case of the effect of an electric field on transport phenomena in rarefied gases of polar molecules, since effects of this type are due to a single

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