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PLASMA INTERACTIONS

Mechanical Effects in a Rarified Plasma

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Abstract—A study is made of various mechanical effects that arise in a rarified plasma and set macroscopic solid bodies into motion: the magnetomechanical effect, the mechanical surface effect, the attraction of macrobodies, the levitation of a body in a plasma, and the orientation of a levitating body. Attention is focused on the design and construction of relevant experiments and experimental tests, as well as on the interpretation of the phenomena observed. Possible applications of the mechanical effects in physics and engineering are discussed.

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1. INTRODUCTION

Studies of plasma interactions with solid surfaces are important from both a fundamental and a practical point of view. These interactions play a governing role in technical problems concerning the structure of electrode sheaths, the protection of the walls of fusion and plasmochemical devices from damage by plasmas, the neutralization of the charge of space vehicles during the injection of charged particle beams in ionospheric and space experiments, etc., and are the primary subject of the theories of electric probes and thermionic converters, dusty plasma theory, and others. In contrast to electrostatic, thermal, and chemical effects occurring in the interaction of a plasma with a solid surface, which have been described in the literature in sufficient detail (see [1–7] and references therein), mechanical effects have received virtually no study.

It can be readily concluded that high-pressure plasmas and high-enthalpy jets can produce very strong mechanical action. This can be illustrated by the following examples. In [8], a pendulum with a mass in the form of a cavity with a hole was used to measure the momentum of a high-power laser plasma jet from the angle of its deviation from the equilibrium position. In [9, 10] (see also the literature cited therein), some schemes were proposed for plasma-torch conversion of laser and microwave energy into the kinetic energy of solid bodies.

The mechanical effects in the interaction of a rarified plasma with a solid body at a pressure p much lower than the atmospheric pressure p_a are less pronounced, however. Nevertheless, there are a number of original works (carried out a few decades ago, as well as in recent years) in which various mechanical actions (effects) exerted by a rarified plasma on solid bodies were revealed. These effects set macroscopic objects into motion and are usually of a kinetic nature: an important issue in their interpretation is a transformation of the distribution function of some group of particles in a plasma. The purpose of the present paper is to give a systematic description of such effects.

It should be noted, first of all, that a distinctive feature of the mechanical effects in a rarified plasma is that the forces exerted by them on the sensitive elements are weak. This required careful development of the measurement methods and the design of measurement units. In most cases, however, we were unable to uniquely interpreted the measurement results. Hence, in order to choose between possible alternative explanations of the mechanical effects, we were to check and validate each measurement result against the results of many test experiments and this sometimes changed our theoretical views about the processes under study. This is why we thoroughly describe here the schemes of measurements and experimental tests and try to demonstrate how the views about the mechanisms responsible for the mechanical effects revealed were reconsidered.

These effects are important for fundamental plasma physics. It is also anticipated that they will have numerous applications in physics and technology (for new plasma diagnostic systems and solar plasma sails as spacecraft propulsors) with potential for dusty plasma physics, technologies for manufacturing artificial flock materials, etc.

2. MAGNETOMECHANICAL EFFECT IN PLASMA

It was predicted in [11] and revealed in [12, 13] that, at gas pressures p as low as a few millitorrs, the gas in the positive column of a discharge in a constant longitudinal magnetic field should rotate about the column axis. If there is a solid plate within the positive discharge column, then the gas will set it into rotation.

The experimental scheme was as follows (see Fig. 1). A positive column discharge column was produced in a vertically oriented tube with electrodes at both ends. The power supply circuit allowed us to change the polarity of the discharge current. The upper electrode had a hole, through which a 20-μm-diameter 30-cm-long quartz filament was inserted downward along the tube axis. The filament carried a vertically suspended rectangular mica plate with a centrally glued mirror, which made possible observation of the plate position by measuring the deviation of the reflected light ray with a graduated scale. In fact, such a suspension is the simplest torsion pendulum with a rigidly fixed upper point—a mechanical system that is most sensitive in measuring weak forces [14].

A pair of ring coils were put on the tube, separated by a small gap to transmit a light ray. A constant magnetic field produced within the tube by the coils was parallel to the tube axis and to the discharge current. The degree to which the field was uniform along the tube axis was at least 97%. The coils were made coaxial with the tube by pulling their bases into a horizontal position by adjustment screws.

In studying noble-gas (Ar and Ne) plasmas at discharge currents of up to 200 mA, Granovskiĭ and Urzakov [12] made the following observations.

(i) In a constant magnetic field, a plate suspended in a plasma turned around its initial position and executed oscillations about the new equilibrium position. After the oscillations were completely damped, the plate remained turned relative to its initial position through a constant angle. At a magnetic field of 100–800 Oe, the deviation reached several degrees. The steady nature of the deviation in a mechanical system with a permanent restoring force (the torsional elasticity of the filament) provided evidence that the effect in question was attributed to a constant magnetic field rather than to eddy electric fields produced when the current in the coils was switched on.

(ii) When the magnetic field was reversed, the plate turned in the opposite direction.

(iii) In contrast, when the discharge current in the tube was reversed, the plate turned in the same direction. This indicates that the effect was not caused by the imperfect parallel orientation of the magnetic field and plasma current.

Granovskiĭ and Urzakov [12] suggested that the observed effect was caused by the rotation of the positive discharge column about its longitudinal axis in a magnetic field. The rotation in turn sets in due to the Hall diffusion current—the diffusion of plasma electrons and ions in a direction transverse to the field and the plasma density gradient. In cylindrical geometry, the plasma density varies only in the radial direction, so the Hall diffusion currents of the electrons and ions should flow azimuthally in opposite directions. Since the momenta of these currents are different, they impart a nonzero angular momentum to the gas and to the plate.

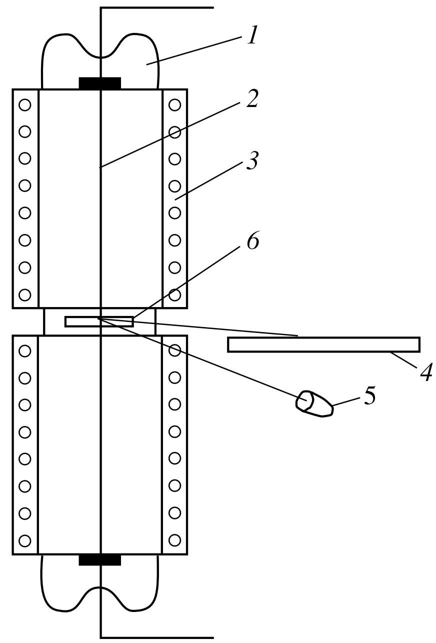

Fig. 1. Scheme of the experiments [15] on the magnetomechanical effect: (*1*) discharge tube, (*2*) filament, (*3*) current-carrying coil, (*4*) scale, (*5*) light source, and (*6*) suspension.

Urzakov [15] carried out more detailed measurements of the effect revealed in [12]. In his experiments with He, Ne, Ar, and Xe discharges, the quartz filament was 30 μm in diameter and 60 cm in length, so the torsion pendulum was more sensitive.

He found that the angular momentum turning the pendulum increases monotonically with both magnetic field and plasma density (discharge current) and that the magnetic effect increases with decreasing gas atomic number. As for the dependence of the effect on the gas pressure, it is nonmonotonic and has a maximum at a pressure independent of the magnetic field strength (at $p \approx 110$ mTorr for argon). The corresponding dependences from [15] are shown in Figs. 2–5.

In [15], the magnetomechanical effect was also observed in RF discharges initiated by a 1-MHz 1-kW RF oscillator in argon at a pressure of $p \approx 125$ mTorr and a magnetic field strength of 250 Oe.

The suggestions made in [12] turned out to be not quite right because experimental results were revealed that fell out of the hypothesis proposed in [12].

The history of research on magnetomechanical effect can be briefly described as follows. Zakharova et al. [16] carried out spectroscopic observations of a discharge column in a magnetic field. Their experiments were performed with a 15-mm-diameter 180-cm-long discharge tube filled with a plasma-producing gas (argon) at a pressure of 0.5–2.5 Torr in a magnetic field of 250, 600, and 1000 Oe, the discharge current

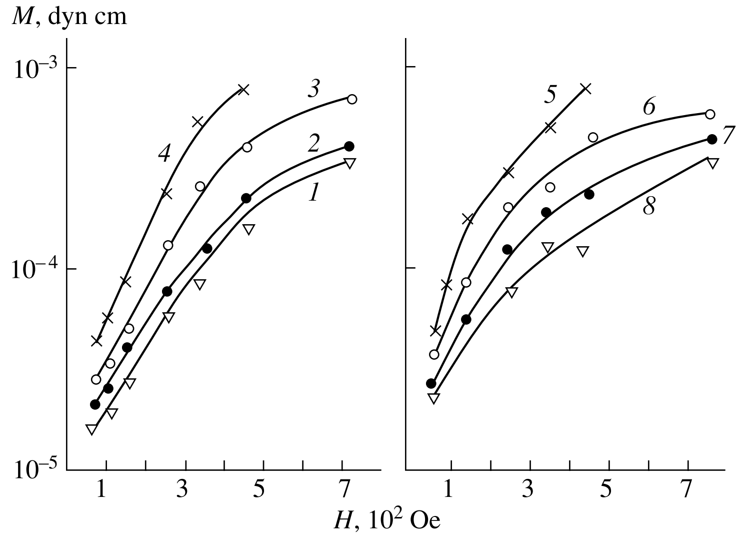

Fig. 2. Magnetomechanical angular momentum vs. magnetic field strength at different argon pressures [15]: (*1*) 0.31, (*2*) 0.28, (*3*) 0.235, (*4*) 0.14, (*5*) 0.094, (*6*) 0.077, (*7*) 0.047, and (*8*) 0.031 Torr.

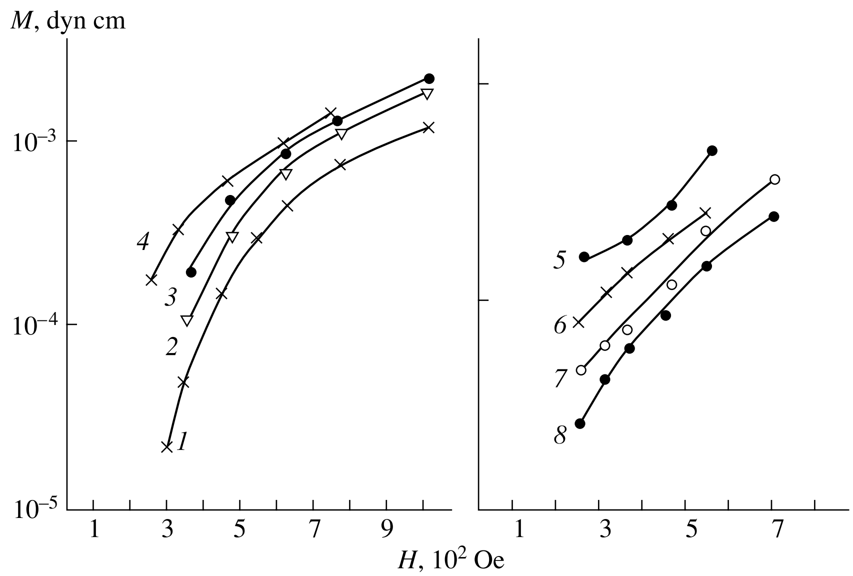

Fig. 3. Magnetomechanical angular momentum vs. magnetic field strength at different neon pressures [15]: (*1*) 0.325, (*2*) 0.275, (*3*) 0.235, (*4*) 0.15, (*5*) 0.085, (*6*) 0.049, (*7*) 0.039, and (*8*) 0.033 Torr.

being 1.6 A. The observations were made by focusing the image of the tube end on a special vaiable-width slit of the spectroscope combined with a Fabry–Perot etalon, which, being tuned to the corresponding spectral line, made it possible to obtain two contiguous images of the same emission line that were recorded at opposite directions of the expected rotation of atoms or ions. The measurement scheme was described in detail in [17]. The experiments showed that the neutral gas did indeed rotate and yielded the following results:

(i) no shift of the lines emitted from the central discharge region was observed;

(ii) the emission lines from the discharge periphery were shifted in opposite directions;

(iii) when the magnetic field was reversed, the lines were shifted in the opposite direction; and

(iv) when the discharge current was reversed, the lines were shifted in the same direction.

The relevant data from [17], namely, the corresponding dependences for atoms of different gases, are shown in Fig. 6. It was also found that the ion rotation velocity determined from the measurement results can be as high as 150 m/s.

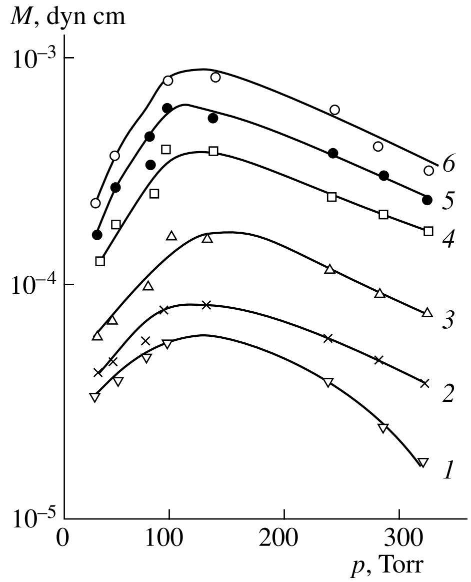

Fig. 4. Magnetomechanical angular momentum vs. argon pressure at a discharge current of 0.2 A and different magnetic field strengths [15]: (*1*) 75, (*2*) 100, (*3*) 150, (*4*) 250, (*5*) 340, and (*6*) 450 Oe.

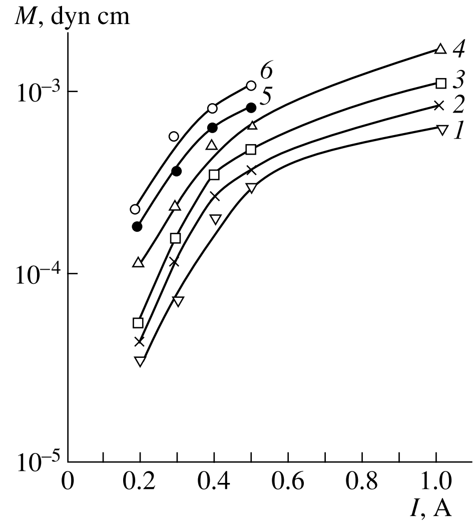

Fig. 5. Magnetomechanical angular momentum vs. discharge current at an argon pressure of 0.047 Torr and different magnetic field strengths [15]: (*1*) 75, (*2*) 100, (*3*) 150, (*4*) 250, (*5*) 340, and (*6*) 450 Oe.

Karasev et al. [18] measured the radial distribution of the neutral gas density in a discharge by a two-ray interferometer. They observed that, in discharges in a magnetic field, the gas escaped from the axial region toward the periphery. This escape can be attributed to the centrifugal forces of gas rotation caused by the magnetomechanical effect. Another possible explanation is the change in the radial temperature profile.

However, unexpectedly, spectroscopic investigations [19, 20] of the magnetomechanical effect that were carried out later in order to check the results of [16, 17] did not reveal any gas rotation: the gas rotation velocity, even if it was nonzero, did not exceed the sensitivity of measurements, 15 m/s. The reasons for such a disagreement still remain unclear because the rotation of suspension was also observed in [18, 19].

Another attempt to understand the magnetomechanical effect was made by Dzlieva et al. [21–23], who contaminated the discharge plasma with dust in order to observe plasma rotation about the discharge axis by a laser Doppler anemometer. They observed the rotation of dust grains suspended in striations around the neck of the discharge column, where the electric current density had a nonzero radial component and, consequently, the gas was subject to a nonzero Ampère force, which put it into rotational motion. In fact, in a longitudinally uniform plasma column, the current has no radial component and, accordingly, there are no volume forces that initiate rotation. Presumably, the magnetomechanical effect stems from the fact that, in [12, 15], the suspension played the role of a neck that formed the current density distribution with a nonzero radial component. The present-day view about the nature of the magnetomechanical effect rests on this presumption, which was described in [21].

3. MECHANICAL SURFACE EFFECT IN PLASMA

In this section, we consider another mechanical effect in rarified plasmas that was revealed in [24]. The nature of this effect is associated with the specific features of the interaction of charged particles with various surfaces. The scheme for its detection with a torsion pendulum is similar to that for recording the above magnetomechanical effect.

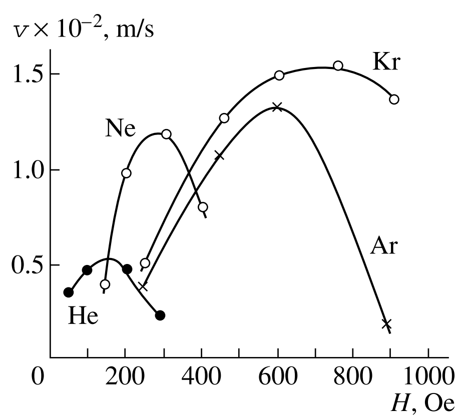

Fig. 6. Data from [17]: the rotation velocity of the atoms of different gases vs. magnetic field strength at a pressure of 1 Torr and discharge current of 600 mA.

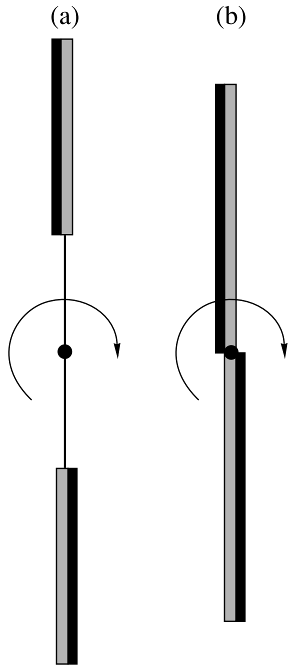

Fig. 7. Coated suspensions used (a) in [25] and (b) in [24].

The idea of the relevant experiments originated from a methodological note by Stasenko [25], who theoretically considered the behavior of a specially suspended torsion pendulum in a model gas. According to [25], let we have a sheet material one of whose surfaces reflects the gas particles elastically, while the other does not reflect them at all (the particles adhere to it). We cut two equal-area plates out of the material and put them on a rod so that they are oriented at an angle of 180° relative to one another. We thus have a suspension, which can be attached to the filament of a torsion pendulum (Fig. 7a). In an inelastic collision, a gas particle transfers to a plate one its momentum, whereas in an elastic collision, it imparts two its momenta. The result is that the suspension of the pendulum experiences a torque, which sets the pendulum into rotation.

We were interested in finding out how this effect is produced by plasma ions, because the momentum imparted to a body surface by them is, as a rule, two to three orders of magnitude greater than that imparted by electrons.

To do this, we built a suspension simpler than that described in [25]. As a sheet material, we used xerox paper with a surface density of 80 g/m^2 and coated it with various conducting (graphite in the lead of a Friendship 6810 HB pencil) and nonconducting (soot from partial combustion of polyamide (plexiglass), white chalk, or black toner powder for the standard cartridge of a Canon LBP-800 laser printer) substances, as is shown in Fig. 7b. Of course, the uncoated and coated sides of the paper have different probabilities of elastically reflecting the plasma ions. If these probabilities

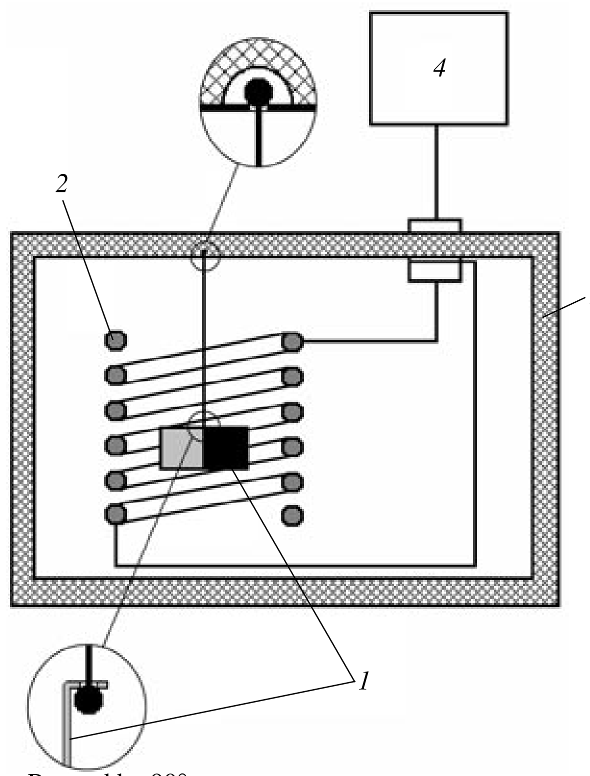

Fig. 8. Schematic of the experiments of [24]: (*1*) suspension of a torsion pendulum, (*2*) inductor, (*3*) gas-discharge chamber, and (*4*) RF generator. The insets show how the pendulum was pivoted to the chamber.

differ appreciably, then it is possible to record a macroscopic mechanical effect that gives rise to a torque.

The filament of the pendulum was made of a Kapron fishing line 100 μm in diameter and 55 mm in length, and one its end was attached to the center of the base of a plate. The other end was pivoted to the chamber wall, and the suspension was attached to the filament in the same fashion (see the insets in Fig. 8). The pivot heads were made as follows. The end of a filament was tied in a bungle, which was then fused in the naked flame of a gas torch. The possible torsion of the filament was controlled by special marks drawn on each of the pivot heads. Experiments showed that the filament so attached was essentially torsion-free and, unlike in [10, 12], a turn of the plate did not give rise to any restoring force.

Experiments were carried out with a hermetically sealed dielectric chamber (Fig. 8) with observation windows. The chamber was equipped with an inductor in the form of a cylindrical helical coil made of a copper wire 2 mm in diameter. The inductor had 10 turns with a diameter of 35 mm, the pitch of the inductor being 10 mm. The chamber was evacuated to a pressure of 0.01–1 Torr, and a steady cylindrical RF inductive discharge was initiated inside the inductor by powering it from a 13.56-MHz IKV-4 medical-purpose oscillator with a controllable power of up to 200 W. The plasma density in the discharge was measured by a double probe.

The suspension of the pendulum was set at the center of the inductor. The turning angle of the suspension in the plasma was determined with the help of a trigonometric circle fixed at the bottom of the chamber.

We found that the suspension turned about its axis through a certain angle, which depended on the gas pressure, the plasma density, the total area of the plate, and the type of coating. The direction of the turn showed that the force acting on the uncoated surface of the paper was stronger. In test experiments, a paper plate whose sides were both uncoated did not turn.

The measurement results are exemplified in Fig. 9, which displays how the turning angle of a pendulum with a suspended rectangular plate having a base of 20 mm and a height of 10 mm depends on the plasma density at a residual gas pressure of 0.05 Torr. Our experimental results show that, first, the effect in question is most pronounced for a chalk coating and, second, that the turning angles were essentially the same for dielectric and conducting coatings.

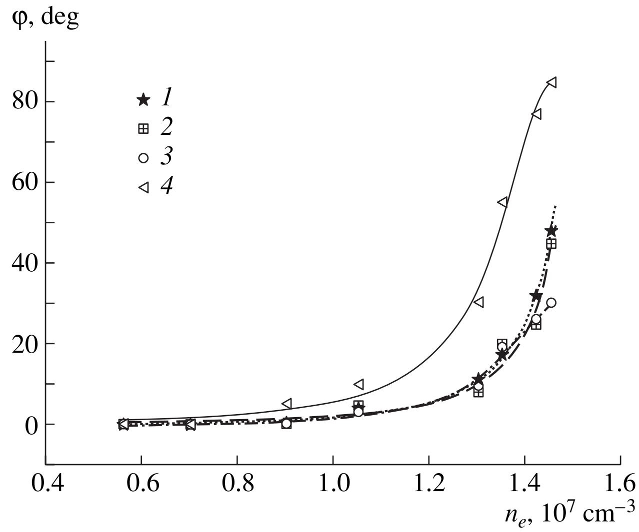

Fig. 9. Turning angle of a pendulum vs. plasma density for plates coated with (*1*) graphite, (*2*) toner powder, (*3*) soot, and (*4*) white chalk.

It is also of interest to point out the following aspect of the effect revealed: why did we observe no steady rotation of the suspension? In the methodological note [25], this question for a nonionized gas was answered by recalling that a perpetuum mobile of the second kind is impossible.

But the effect observed in our experiments may offer a more adequate physical explanation. Note first of all that, in an open system such as a plasma, steady rotational motions are consistent with the laws of thermodynamics. It is known, however, that, in a weakly ionized low-pressure gas-discharge plasma, a solitary body acquires a large negative electric charge [26] due to the high electron mobility. Immediately after a discharge is initiated, when the plate is still electrically neutral, the torque arises in the way described above. As the negative charge is accumulated on the plate, the ions that fly up to the plate are greatly accelerated, so the probabilities for different coatings to absorb them become the same. As a result, the torque vanishes and the plate stops rotating owing to unavoidable friction in the pivot heads of the pendulum. The charging time is usually on the order of the reciprocal of the ion Langmuir frequency. Consequently, the Langmuir period is the time scale on which the torque is efficient (the ion impact time).

This explanation is confirmed by the following observations. When a discharge was switched off for a short time period and then was switched on again, we observed no turn of the pendulum. However, when the electric charge accumulated on the plate was neutralized, e.g., by puffing moist atmospheric-pressure air into the chamber and by treating the pendulum in such conditions for no less than 20 min, after which the chamber was evacuated, we could again observe the pendulum turning. The reproducibility of the measurement results in these experiments was quite satisfactory.

In investigating the effect revealed, we also originated an alternative working hypothesis that the suspension can turn due to the reactive force resulting from the gas desorption, which, in turn, can occur due to the heating of the plate surfaces in the discharge. This hypothesis rests on the observation that the suspension turned only after the chamber was decompressed, in which case the surfaces of the plate could be saturated with air.

The hypothesis was carefully checked. We found that the structural elements of the chamber and suspension were heated insignificantly (their temperature increased by several degrees). We also carried out a special series of experiments with a suspension made of a 3-μm-thick aluminum foil one of whose sides was coated with soot as shown in Fig. 7b. The plate was suspended on a copper wire whose upper end was linked to a connector in the chamber wall in order for the suspension could be grounded during the intervals between the discharges without decompressing the chamber. The suspension was observed to turn each time the discharge was switched on, so we were justified in excluding the desorption-induced pulsed reactive force from the main forces governing the mechanisms for the effect under study.

The mechanical surface effect considered in this section can be utilized to measure the differences between the probabilities of elastic ion scattering by various solid materials.

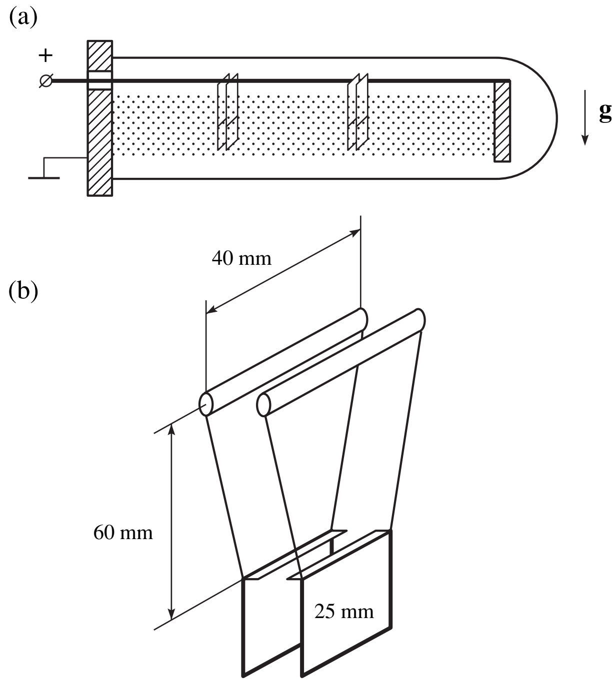

Fig. 10. Scheme of experiments on the attraction of macrobodies [39]: (a) discharge chamber and (b) suspension of the plates.

4. ATTRACTION OF MACROBODIES IN PLASMA

It is known that, under certain conditions, dust grains in plasma can arrange themselves into ordered structures—so-called dust–plasma crystals [27–29]. The grains in plasma can acquire certain equilibrium electric charges of the same sign (as a rule, they are charged negatively); consequently, at distances shorter than the Debye radius, they should repulse one another because of their Coulomb interaction. However, at long distances, dust grains should be subject not only to repulsive but also to attractive forces, which prevent dust–plasma crystals from decaying. At this point, it should be noted that uniform crystalline structures of like-charged particles in a closed container or in an infinite space can form without any long-range attractive forces, but, for finite-size crystalline structures with a free boundary that were observed experimentally in [29], it is worthwhile to search for the attraction mechanisms.

In the literature, a number of theoretical papers have appeared in which several different mechanisms for the onset of attractive forces were proposed and investigated:

(i) the attraction mechanism that is associated with the asymmetry of bombardment of a dust grain by plasma particles and results from the shadowing of the plasma flux to a grain by the neighboring ones (an analogue of the LeSage kinetic model of gravity [30, 31]),

(ii) attraction associated with the Coulomb scattering of charged plasma particles by charged grains [32],

(iii) attraction due to thermophoresis of dust grains in a plasma [33],

(iv) attraction due to ion-acoustic wave coupling [34] (a classical analogue of Cooper electron pairing in superconductivity theory), and

(v) attraction due to wave coupling (a classical analogue of Casimir forces [35]).

The mechanisms for attraction of dust grains in plasma were reviewed in [36, 37]. In [38, 39], attempts were made to directly observe such attraction of macroscopic bodies.

Of course, investigation of attraction between dust grains by direct observations is a complicated matter because of their small size. This is why it is convenient to perform measurements in experiments with one-dimensional (thin filaments) or two-dimensional (thin films) analogues of grains. In [38], two polyester films freely suspended in plasma in the Earth's gravitational field were indeed observed to attract one another and it was found that the attractive forces became stronger as the degree of plasma ionization increased at a constant pressure.

However, in those experiments, the measurement error was too high and the reproducibility of the results obtained was poor. This is explained by the heating of films: shortly after the films began to be acted upon by the plasma, they became collapsed or twisted, i.e., nonplanar, and had often to be replaced with new films. In turn, imperfect suspension of new films due to the uncontrolled deviation from the vertical position resulted in a considerable spread in the measured magnitudes of the attractive forces. In addition, in [38], the question of the attraction of metal objects was not clarified.

In [39], measurements were made at a qualitatively new level. As in [38], the experiments were carried out with a thin-walled glass discharge chamber 180 mm in diameter, the length of the interelectrode gap being 700 mm (Fig. 10a). The chamber was placed horizontally in order for the objects freely suspended in the chamber to be oriented perpendicular to the discharge current.

The air pressure in the chamber was held at a level of 10–100 mTorr. Steady dc glow discharges were initiated between the electrodes of the chamber. The plasma parameters were determined from probe measurements.

In the experiments, 25 × 25-mm dielectric (xerox paper with a surface density of 80 g/m^2) and metal (an aluminum foil with a surface density of 67.8 g/m^2) plates were suspended on 80-μm-diameter copper wires. The arrangement of the suspensions (see Fig. 10b) provided a sufficiently high sensitivity of measurements and prevented the plates from rotating about their vertical axes.

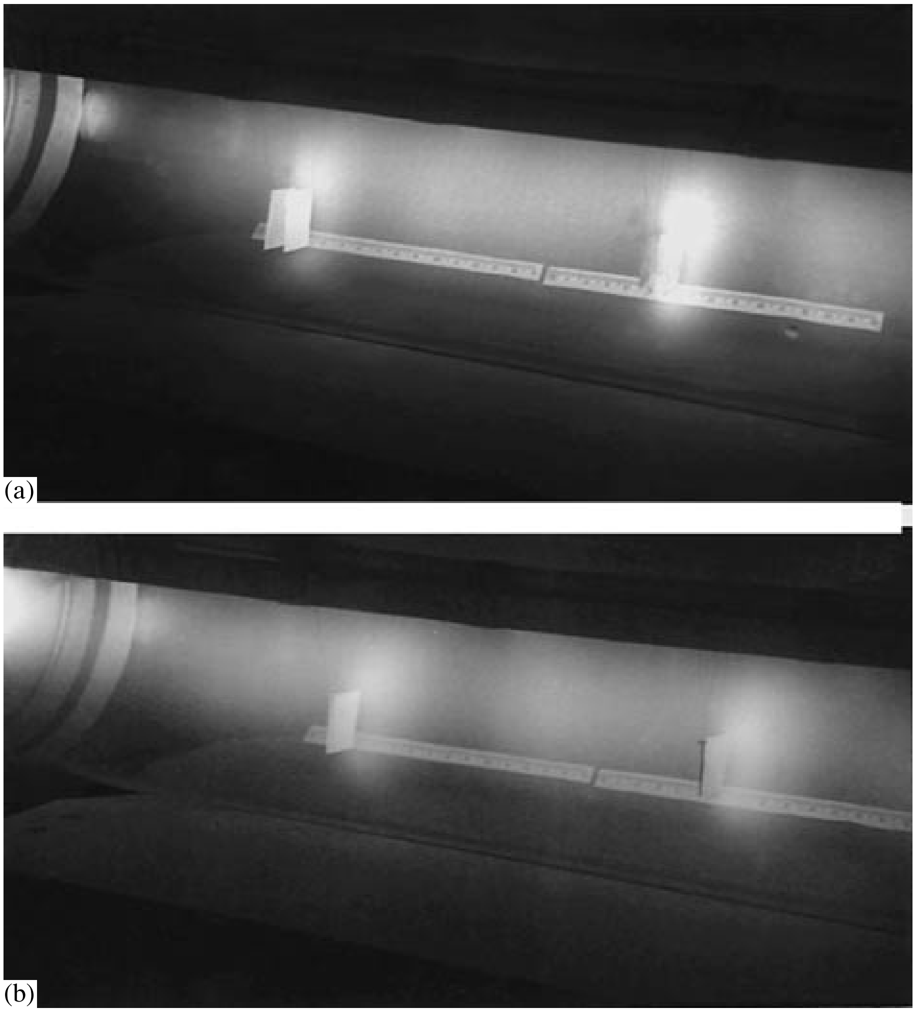

Fig. 11. Photographs of the plates in a discharge plasma [39] (a) at a minimum discharge current (the plates are suspended freely) and (b) at a discharge current of ~0.5 A (the plates are in the closest position relative to one another).

Figure 11a shows photographs of freely suspended plates in a low-current discharge. As the discharge current (and accordingly, the plasma density) was gradually increased, the plates approached one another so that their edges nearly touched one another (below we will show, however, that they did not come completely in contact). The situation at a maximum discharge current is shown in Fig. 11b. We measured the distance between the approaching plates as a function of the discharge current and put the magnitudes of the discharge current into correspondence with the values of the electron density obtained from probe measurements. The interplate distance so obtained, as well as the corresponding attractive force, is presented in Fig. 12 for paper and aluminum plates as a function of the electron density.

It should be noted that the plates also approached one another in a nonuniform discharge in its standing striations that occurred at certain pressures and currents; in this case, however, the reproducibility of the measurement results was worse than in uniform discharges.

After the discharge was switched off, the plates were observed to repel one another. This provides evidence that, in the course of a discharge, the plates acquired significant electric charges of the same sign.

Note also that, when the plates were short-circuited externally, they attracted one another in precisely the same manner as above, which gives evidence of a nonelectric nature of the attraction.

The electric potential of the aluminum plates was approximately equal to the potential of the positive discharge column. As the plasma density was increased, the potential difference between the plates first increased to 1.15 V and then decreased to 0.6 V as the plates approached one another. We thus can conclude that there was a certain minimum distance between the plates, which, according to estimates, was on the order of the Debye radius (several hundredths of a millimeter). This can be explained by the fact that, at shorter

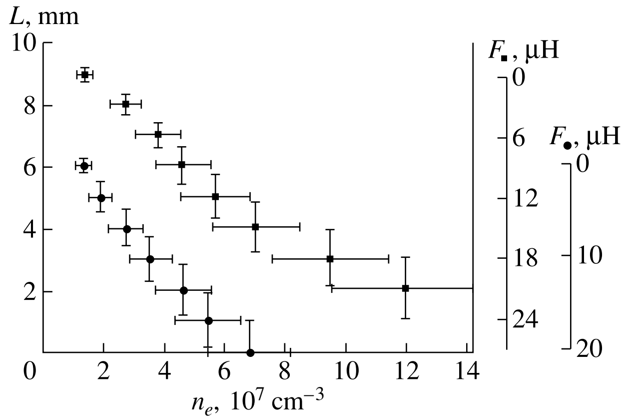

Fig. 12. Attractive forces between the grains and intergrain distance vs. plasma density in the experiments of [39]: the circles and squares are for paper and aluminum plates, respectively.

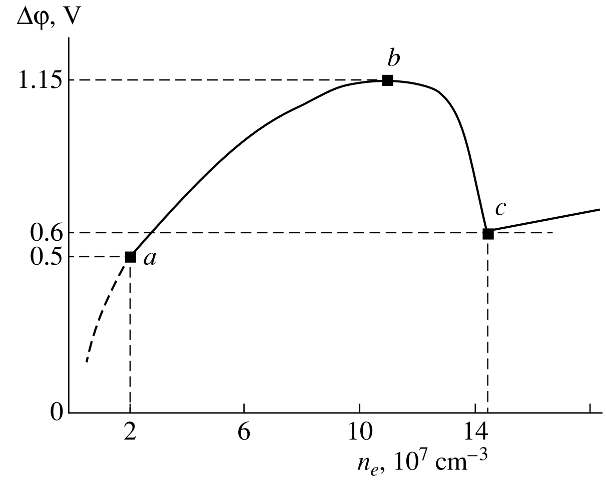

Fig. 13. Potential difference between aluminum plates vs. plasma density (according to the results of [39]).

distances, the electrostatic repulsive forces predominate over the attractive forces. The potential difference between aluminium plates as a function of the plasma density is displayed in Fig. 13.

Hence, the experimental results allow us to conclude that, in plasma, closely located macroscopic bodies do indeed interact via nonelectric attractive forces, which govern the dynamics of the bodies. According to estimates [33], these forces are too strong to be explained in terms of the LeSage model but can be attributed the thermophoresis effect.

The attractive forces in question play an important role in dusty plasmas: they can lead to dust crystallization into free-boundary structures, can govern the hydrodynamics of the expansion of a dust bunch in such a way that the expansion rate is slower than that of a dust-free plasma bunch, and can even lead to the self-compression of a dust bunch (see [40, 41])—an effect that is of interest in the context of plasma confinement. Another consequence of the attractive forces is the onset of isotropic surface tension at the boundary of a dusty plasma, in contrast to the anisotropic surface tension at the plasma–magnetic field interface.

Along with its importance for dusty plasmas, the attractive force revealed in [38, 39] can offer additional possibilities for probe measurements in plasma, provided that the probes are freely suspended (see Fig. 10b).

5. LEVITATION OF A MACROBODY IN A MICROWAVE DISCHARGE PLASMA

It is well known that high-pressure microwave discharges are accompanied by intense hydrodynamic phenomena resulting from collisional gas heating [42–44]. In a recent paper by Exton et al. [45], it was shown that, in a low-density gas (at a pressure of $p < 50$ Torr), a diffuse microwave discharge heats the gas and raises its pressure, so mechanical forces can be produced and can act on nearby bodies.

Figure 14 shows the layout of experiments on the levitation of a macrobody in a low-temperature diffuse microwave discharge initiated at the surface of the output window of a horn antenna. The antenna had a 5.94×7.94-cm rectangular output window and was excited by a microwave oscillator generating a train of 210-V pulses at a frequency of 9.5 GHz (with an energy of 0.63 J per pulse), the repetition rate being 500 pulses per second. A 4-mm-thick styrofoam disk 4.9 cm in diameter with a weight of 0.18 g was placed on the surface of the output window. In order to stabilize the lifting and levitation of the disk, the horn was equipped with a special wood frame with nylon threads stretched through the disk.

Figure 15 presents a series of photographs taken with a CCD camera with a framing rate of 10 Hz at a gas pressure of 11 Torr. The photographs show different phases of the lifting of the disk from the horn window and of its levitation owing to the pressure produced by the microwave discharge.

This mechanical effect can be used to increase the maximum lifting height of lighter-than-air vessels, which are driven upward by buoyancy force, such as dirigibles, stratosphere and weather balloons, and so on.

6. ORIENTATION OF LEVITATING MACROBODIES IN PLASMA

Here, we describe one more experimentally revealed mechanical effect in a rarified plasma. The technologies for manufacturing artificial flock materials most often utilize methods of precharging fibers in atmospheric-pressure corona discharges and their subsequent deposition at a given angle onto a glue substrate in an external electric field [46, 47].

Recent experiments on the orientation of fibers in plasma [48] have demonstrated that such technologies can also use low-pressure glow discharges. It was found that nylon fibers 7.5 and 15 μm in diameter and 300 μm in length were easily oriented perpendicular to the discharge axis at a pressure of 0.1 Torr. Note that glow discharges hold great promise for manufacturing artificial flock materials because they make it possible to substantially raise the production efficiency at the expense of a larger surface onto which fibers can be simultaneously deposited and to appreciably increase the quality of the resulting flock materials at the expense of the homogeneity of the discharge plasma.

On the other hand, the fibers used in [48] were much smaller in size than those used for industrial flocking. The objective of [49] was to experimentally investigate the possibility of orienting larger fibers in glow discharges and to develop methods for extracting oriented fibers from the discharge region and for depositing them onto glue substrates, as well as methods for controlling their orientation angle with respect to the substrate surface.

The experiments in [49] were carried out with a specially devised chamber shown schematically in Fig. 16. The chamber was a 10 × 10-cm rectangular dielectric tube 70 cm in length. Two steel electrodes with an area equal to the cross-sectional area of the tube were installed at the tube ends. In the experiments, the tube was oriented horizontally.

A high-precision needle injector capable of injecting fibers either one by one or several thousands at once was installed in the upper wall of the chamber. In earlier experiments, this injector was used to study the properties of a dusty plasma. The design of the injector and its operating modes were described in detail in [50].

As a glue substrate, we used a transparent cellophane film with a glue layer on one side (a commercial Rusi Star scotch tape). The tape was placed on a specimen stage at the bottom of the chamber so that its glue side faced upward, toward the injector of fibers (Fig. 16). The working surface of the substrate was 10 × 10 cm in size.

As fibers, we used portions of Kapron threads 100 μm in diameter and 3 mm in length. Such fibers were about 1000 times heavier than those used in [48]. In the experiments reported here, the fibers were injected into the plasma one by one.

The experimental results were as follows. When the fibers were injected into an unionized gas at a pressure from ~0.1 Torr to atmospheric one with no discharge initiated, they were observed not to be oriented and fell down on the substrate to lie there horizontally at random angles to the tube axis.

In contrast, when the fibers were injected into a steady uniform glow discharge at a current of 250 mA (Fig. 16a), they fell down strictly vertically to orient themselves transverse to the discharge axis, as was observed in [48]. After the fibers had reached the substrate, their lower ends were glued to it and the fibers themselves remained in the vertical position for an arbitrarily long time. The fibers glued to the substrate are shown in an enlarged fragment of the photograph in Fig. 17a.

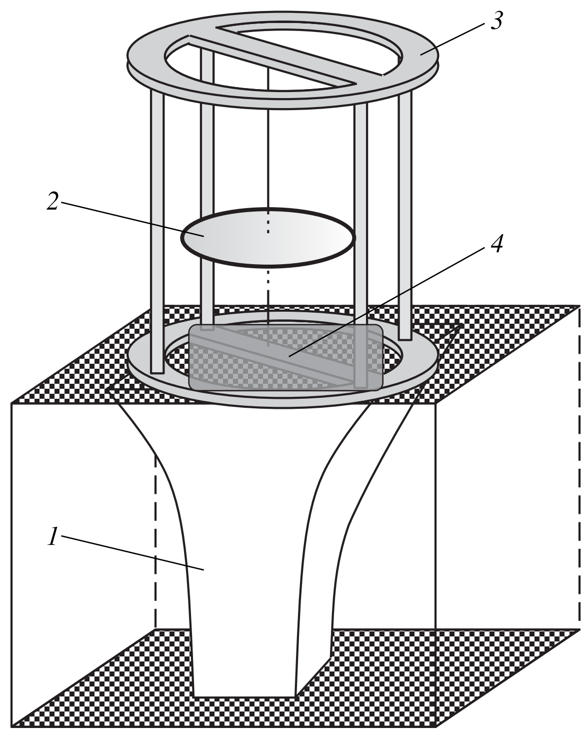

Fig. 14. Scheme of experiments on the levitation of a macrobody in a microwave discharge plasma [45] (by permission of the American Institute of Physics): (*1*) horn antenna, (*2*) levitating disk, (*3*) wood frame, and (*4*) surface plasma of a microwave discharge.

That the fibers orient themselves transverse to the discharge axis can easily be explained by comparing the longitudinal and transverse components of the electric field in the discharge. The longitudinal component is known to be as weak as 10–20 V/cm [51], while the transverse component, which is associated with the plasma density gradient near the dielectric wall of the chamber, can be as strong as a few hundred volts per centimeter.

These experimental results yield a simple method whereby the orientation angle of the fibers can be controlled as they fall down on the substrate, specifically, by changing the direction of the transverse plasma density gradient near the substrate surface with the help of a transverse limiter (see Fig. 16b).

We used a dielectric limiter with a circular opening. By varying the opening diameter and the distance from the limiter to the fiber injection plane, it is possible to prespecify the angle between the plasma density gradient and the substrate surface. For instance, when a limiter with an opening diameter of 40 mm is placed at a distance of 80 mm from the injection plane, the maxi-

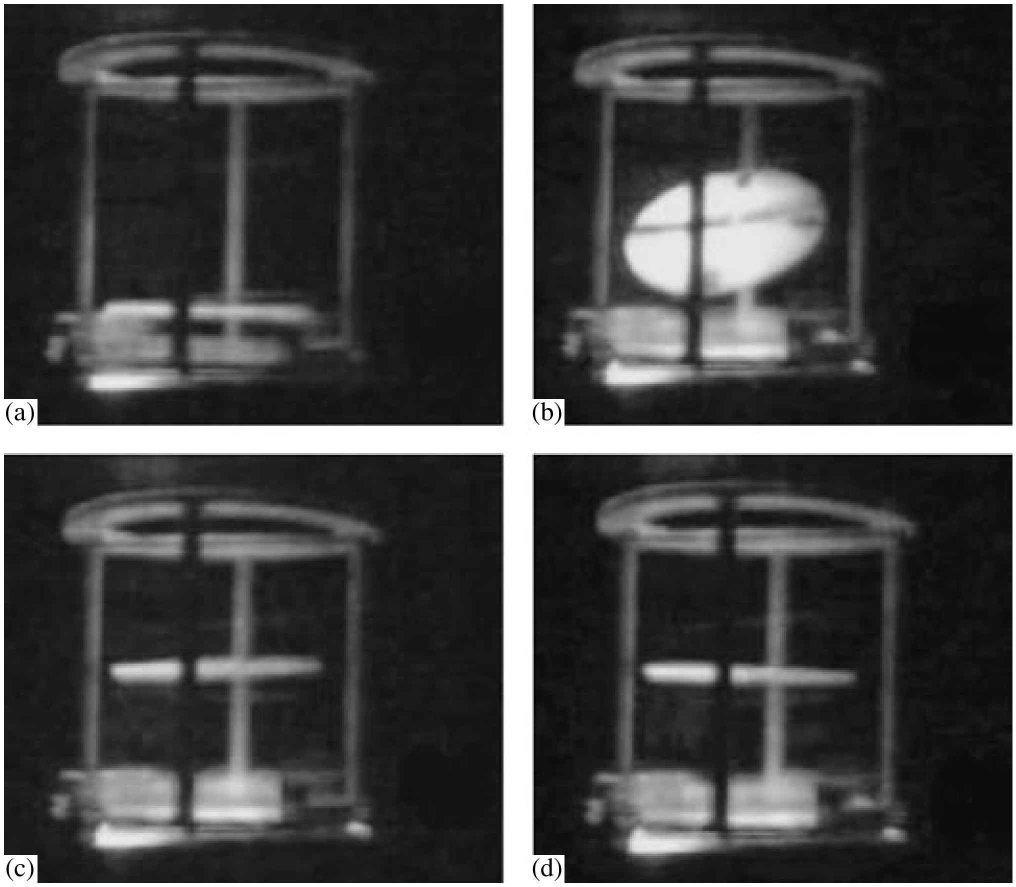

Fig. 15. Photographs of a disk levitating in a microwave discharge plasma [45] (by permission of the American Institute of Physics): (a) before switching on microwave radiation, (b) microwave radiation is switched on ($t = 0$ s) and the disk begins to be lifted up, (c) the disk levitates in a stable position ($t = 7.8$ s), and (d) the position of the levitating disk remains stable ($t = 10.2$ s).

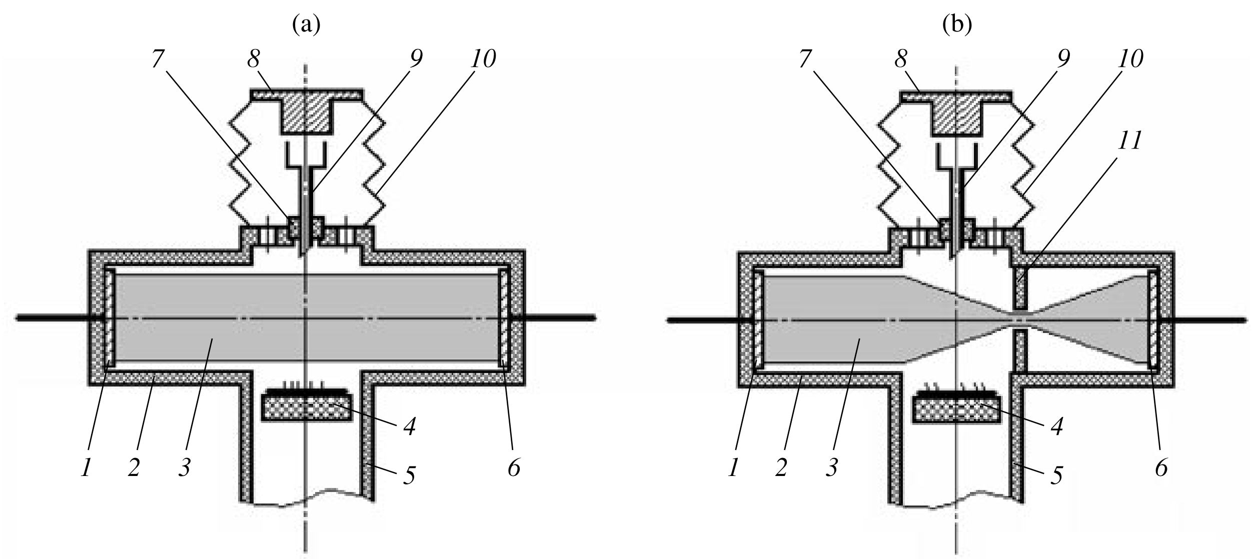

Fig. 16. Schemes of experiments on the orientation of fibers [49] (a) in a longitudinally uniform glow discharge and (b) in a glow discharge with a limiter: (*1*) anode, (*2*) discharge tube, (*3*) discharge plasma, (*4*) specimen stage, (*5*) evacuation port, (*6*) cathode, (*7*) rubber plug, (*8*) pusher, (9) needle injector, (*10*) sylphon, and (*11*) diaphragm.

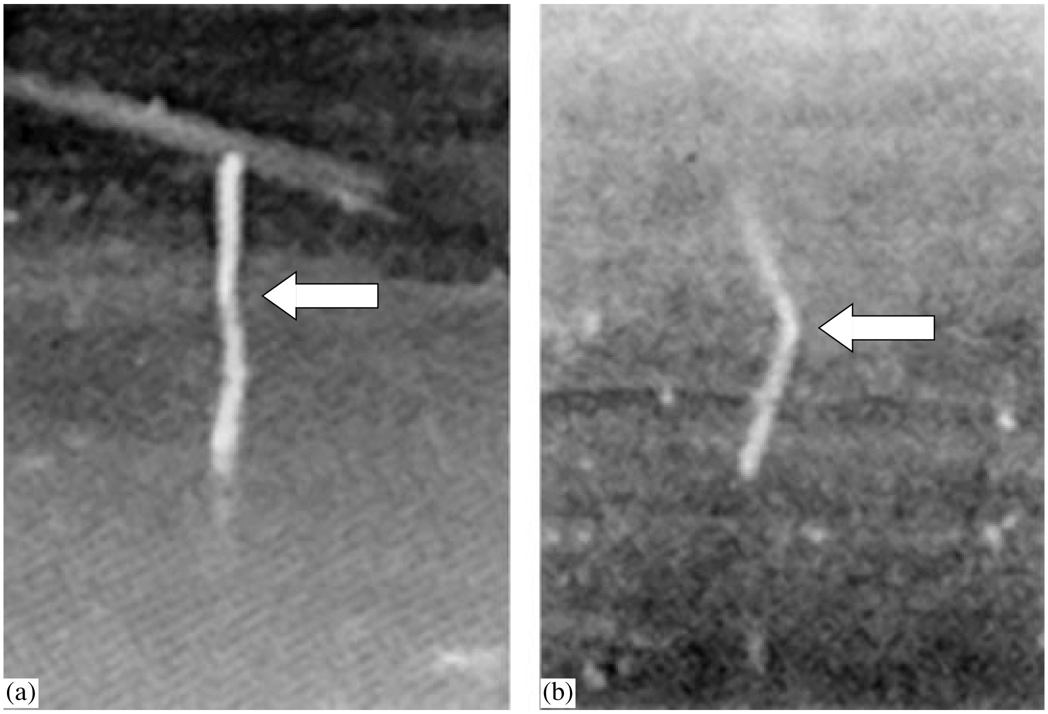

Fig. 17. Photographs of fibers glued to a substrate (reproduced from [49]) (a) in a longitudinally uniform glow discharge and (b) in a glow discharge with a limiter. The arrows show the sites where the fibers are glued.

mum angle between the density gradient and the vertical direction is approximately equal to 70°.

In this case, the fibers fell on the substrate obliquely and became glued to it at approximately the same angle, 70°, with respect to the vertical (see Fig. 17b).

Hence, in [49], it was demonstrated experimentally that flock materials with a given inclination angle of fibers can be produced artificially by depositing fibers onto a glue substrate in a low-pressure glow discharge. In [52], similar studies were carried out in experiments with a low-density plasma of RF inductive discharges initiated in a source like that described in Section 3. The experimental results under discussion may lay the groundwork for new technologies in light industry.

7. CONCLUSIONS

In the present paper, we have reviewed the results of experimental investigations demonstrating various mechanical effects that arise in a rarified plasma and drive macroscopic solid bodies into motion—specifically, the magnetomechanical effect, the mechanical surface effect, the attraction of macrobodies, the levitation of a body in a plasma, and the orientation of a levitating body. Attention has been focused on the design and construction of relevant experiments and experimental tests. Although the mechanical effects revealed in our study still continue to be interpreted, the above examples provide convincing evidence that macrobodies can be set into motion in a rarified plasma. Numerous applications of the mechanical effects in physics and engineering have been mentioned. Hence, we are justified in speaking of a new direction in plasma physics—the mechanics of macrobodies in plasmas, which is closely related to dusty plasma physics.

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