RELAXATION OF ION BEAM INJECTED INTO A PLASMA TRANSVERSELY TO A MAGNETIC FIELD

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The two-stream ion instability excited in a plasma by an ion beam [1, 2] is an effective mechanism of beam relaxation and plasma heating [3 - 6]. However, the free motion of the electrons along the magnetic-field force lines stabilizes the ion-ion instability in a wide range of beam velocities, $V > c_s$ at $\cos\theta^2 > m/M$ (c_s is the velocity of non-isothermal ion sound, θ is the angle between the wave vector $\vec{k}$ and the magnetic field H, and m and M are the masses of the electron and the ion. When the ion beam is injected perpendicular to the direction of the magnetic field ($\theta \sim \pi/2$) and under the conditions

$$k^2\rho_e^2 << 1 << k^2\rho_i^2 \qquad (1)$$

($\rho_{e,i}$ is the average Larmor radius of the electrons or ions), such an instability can develop at beam velocities up to the Alfven velocity, and the plasma need not necessarily be non-isothermal in this case [1, 2, 7 - 10]. The nonlinear theory [7] and numerical experiments [8, 9] show that as a result of the development of longitudinal low-frequency oscillations ($\omega_{Hi} << \omega << \omega_{He}$, where $\omega_{Hi,e}$ is the cyclotron frequency of the ions or electrons) in such a system, the energy of the ion translational motion is anomalously rapidly transformed into thermal energy. We have verified experimentally that an ion beam introduced into a plasma transversely to a magnetic field is effectively thermalized when conditions (1) are satisfied.

The experimental setup is shown schematically in Fig. 1. An argon plasma 1 was maintained with the aid of a discharge with an incandescent cathode in a magnetic field produced by coils 2. The porous tungsten ionizer 3 and the accelerating grid 4 with large negative potential (~500 V) have made it possible to produce a beam of potassium ions and introduce this beam into the plasma transversely to the magnetic field. The beam energy ε was set by the potential difference between the ionizer and the plasma. A moveable electrostatic analyzer 5 has made it possible to investigate the beam velocity distribution function at different distances h from the source. The function was determined by graphic differentiation of the delay curve (the plot of the collector current I_c against the retarding potential u_r). The plasma parameters were determined with a single probe. Typical experimental conditions were: ion beam current ~1 mA, ε = 0 - 200 eV, maximum flight distance h = 15 cm, plasma density $n \sim 5 \times 10^9$ cm^{-1}, electron temperature ~8 eV, argon pressure 10^{-4} mm Hg, and H = 0 - 50 Oe.

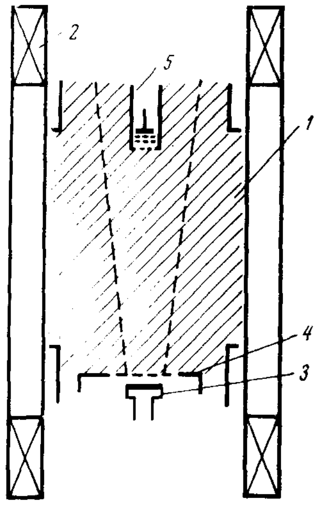

Fig. 1

The experiments have shown that superposition of even a relatively weak transverse magnetic field on the plasma-beam system leads to an effective relaxation of the beam. Figure 2 shows the distribution functions of the beam as functions of the magnetic field intensity (h = 14 cm). In the absence of a magnetic field, the ion beam (ε = 70 eV) practically does not interact with the plasma over the indicated flight path. In a magnetic field H > 40 Oe and under analogous conditions, an effective deceleration of the bulk

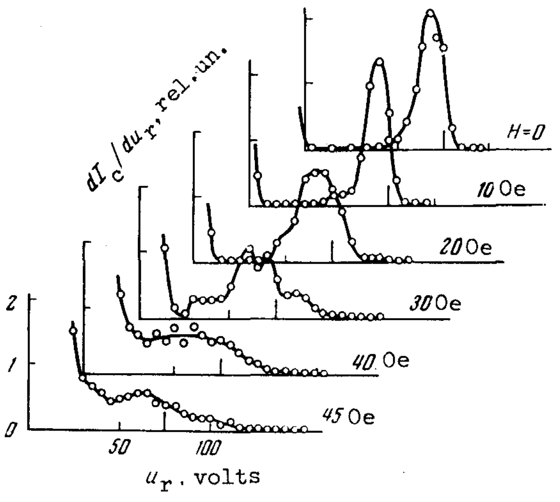

Fig. 2

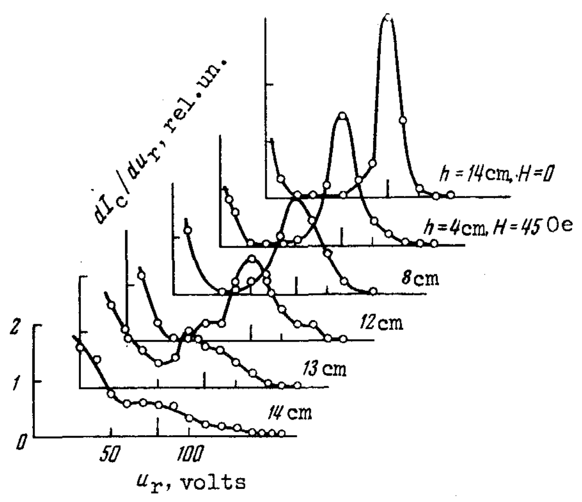

Fig. 3

of the ions is observed, i.e., their energy becomes dissipated in the plasma. At the same time, particles accelerated all the way to double the initial beam energy are observed. Figure 3 demonstrates the spatial development of the deformation of the beam-ion distribution function (H = 45 Oe). The described effects are observed under conditions when a noise spectrum of oscillations of frequency 100 - 500 kHz are excited in the plasma, i.e., in the region of the lower hybrid resonance. The collisionless character of the interaction between the ion beam and the plasma follows directly from the experimental data (upper curves on Figs. 2 and 3) and is confirmed by an estimate of the mean free path of the ions relative to pair collisions (charge exchange, elastic scattering), which exceeds the beam relaxation path by one order of magnitude.

At the indicated values of the magnetic field intensity, the field hardly disturbs the ion motion, but limits of motion of the electrons perpendicular to H, i.e., conditions are produced for the development of ion two-stream instability. The maximum linear hydrodynamic growth increment of the oscillations excited by the ion beam [7, 8]

$$\gamma_m \sim (1/2)\omega(n'/n)^{1/3} = \{\omega_{0i}/2[1+(\omega_{0e}^2/\omega_{He}^2)]^{1/2}\}(n'/n)^{1/3}$$

corresponds to the wave numbers $k_n \sim \omega/V$ (n' is the density of the beam ions, and $\omega_{0i,e}$ is the Langmuir frequency of the plasma ions or electrons). Under the conditions of the experiment we have $\omega_{0e}^2/\omega_{He}^2 >> 1$, and

$$\gamma_m \sim (1/2)(\omega_{He}\omega_{Hi})^{1/2}(n'/n)^{1/3},$$

i.e., the increment increases with increasing magnetic field. An estimate of the spatial scale of the linear development of the oscillations, $L \sim V/\gamma_m = 3.3$ cm (at H = 40 Oe, V = 2 × 10^6 cm/sec, and $n'/n \sim 0.1$ on the average over the flight path) is in qualitative agreement with the observed beam-relaxation length. In this case we have $k_m^2\rho_e^2 \sim 0.1$ and $k_m^2\rho_i^2 \sim 10^2$ if the plasma ion temperature is assumed to be 0.1 eV.

We have thus obtained experimental proof that two-stream ion instability in a transverse magnetic field is an effective collisionless mechanism for the thermalization of an ion beam in a plasma. We propose that such an instability is the main mechanism for heating ions that move with many velocities on the front of a shock wave [11], and is also one of the possible ways of thermalizing fast ions that accumulate in traps in which neutral atoms are injected [12]. In connection with the latter, attention must be called to the fact that a numerical experiment on the quasilinear relaxation, in a plasma, of a group of ions with large transverse energy in two-dimensional velocity space ("random" distribution over the phase shifts of the Larmor rotation) has revealed that the resultant deformation of ion distribution function is similar to that observed in the present study.

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LEVEL SHIFTS AND WIDTHS OF $p\bar{p}$-ATOM

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It was shown in [1] that an experimental determination of the shifts of the S levels of the $p\bar{p}$-atom makes it possible, in principle, to determine the sign of the real part of the $p\bar{p}$ scattering length.

The values obtained in [1] for the level shifts ΔE for the states 1S and 2S turned out to be 0.9 and 0.1 keV, respectively. However, these estimates of ΔE are qualitative in character (the $p\bar{p}$ scattering length was assumed equal to 1 F regardless of the spin and isospin of the $p\bar{p}$ system).

In this paper we calculate the shifts and widths of the S levels (principal quantum number n = 1 and 2) of the $p\bar{p}$ atom in different spin-isospin states, by using the Bryan-Phillips (BF) potential [2] for the nucleon-antinucleon interaction at low energies.

To calculate the level shifts, we use the real part of the BF potential. Allowance for the imaginary part, which corresponds to annihilation effects,