difference from one solution to one another (two orders of magnitude between benzene-chloroform and carbon disulfide–acetone solutions). The results obtained are in reasonably good agreement with those expected, for a nearly ideal solution as well as for a nonideal solution. Thus, the experimental method which we used seems to be useful for the study of deviation from ideality of the solutions.

We wish to thank Dr. Calmettes for many helpful discussions on this subject.

Note added in proof.—Some attempts to measure the activity coefficients of a solution have been made (Refs. 8 and 9) using the Rayleigh-to-Brillouin scattering intensity ratio. But this last method seems more complicated and requires the evaluation of more parameters than in our measurements, and seems less conclusive, according to the authors themselves.

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Experimental Observation of Drift Instabilities in a Collisionless Plasma

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Pressure-gradient–driven drift waves have been identified in a collisionless ($n_0 = 10^{10}$ cm^{-3}, $T_e = 10$ eV), 5.4-m-long, hydrogen plasma. Measurements show large but finite parallel wavelengths and short transverse wavelengths as predicted by the theory. For these wavelengths, computations give the maximum linear theoretical growth rate.

A low-β, collisionless, inhomogeneous plasma contained in a magnetic field $\vec{B}_0$ will be unstable to low-frequency electrostatic oscillations.[1] Gradient-driven waves propagate in a direction almost perpendicular to the magnetic field but have a large phase velocity parallel to $\vec{B}_0$, allowing a strong coupling with the parallel motion of the electrons (inverse Landau damping). The experiments reported herein were directed towards the identification of spontaneous oscillations arising in a hydrogen plasma as collisionless drift waves. The frequencies, wave numbers, and density versus potential phase shift of the instabilities have been measured and compared with computations of the linear dispersion relation.

The experimental work has been performed on the ODE device. ODE is a 5.4-m-long vacuum chamber immersed in a homogeneous magnetic field $B_0 \leqslant 3.5$ kG. The steady hydrogen plasma is produced by two sources[2] symmetrically located at both ends of the machine (Fig. 1). Compared with other experiments used in studies of both collisional[3] and collisionless[4] drift instabilities, this device has the following characteristics: (1) All collision frequencies are lower than the frequencies of the observed instabilities by at least a factor of 10; (2) there are no metallic end plates which would quantify the parallel wavelength to the machine length; and (3) the length of the column, 5.4 m, permits the development of large parallel wavelengths.

Most of the measurements (density n_0, electron temperature T_e, plasma potential, and waves) were performed using spherical coaxially shielded Langmuir probes (0.5 mm in diameter). The wave potential was detected with a high-impedance (10^8 Ω) capacitive probe. The ion temperature ($T_i = 2 \pm 0.4$ eV) was measured both by spectroscopy (Doppler broadening of H_β) and with a gridded probe. On the axis of the plasma column T_e is equal to 14 eV and n_0 increases linearly with the source current between 10^9 and 10^{10} cm^{-3}. Both n_0 and T_e exhibit a Gaussian

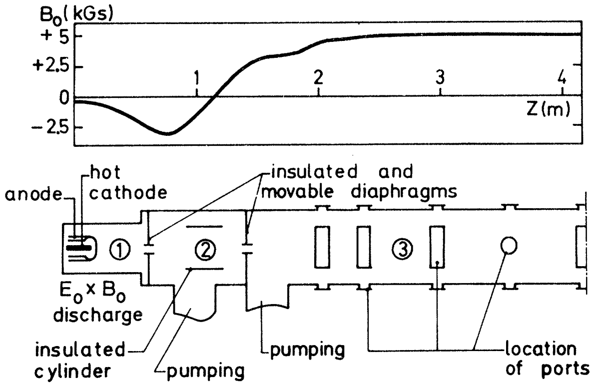

FIG. 1. Schematic diagram of one half of the ODE device. The plasma column is 5.4 m long and the sources are 8.8 m apart. The plasma is created by an $E_0\times B_0$ discharge (see Ref. 2) in compartment 1 ($p_0 \simeq 10^{-3}$ Torr). It diffuses through a diaphragm towards a cusped-field region, 2, and then through a second diaphragm into the main chamber. The differential high-speed pumping ensures a base pressure $p_0 = 10^{-6}$ Torr in the main chamber with the two sources working. This configuration ensures a collisionless regime in the main chamber. Moreover it uncouples the source from the plasma in 3 thus reducing to a low level the instabilities induced by the source in the main plasma. The two sources work symmetrically ensuring a low current parallel to B_0 and a low parallel density gradient.

radial profile with $\nabla n_0/n_0 = \nabla T_e/T_e = 1\ \text{cm}^{-1}$ independent of the magnetic field. At 2 kG, there are 10 Larmor radii ($\rho_i = 1.0$ mm) in the corresponding scale length. Because of the symmetry of the experiment, n_0, T_e, and their radial gradients, $\nabla n_0/n_0$ and $\nabla T_e/T_e$, are found to be constant to within 5% in the direction parallel to the column axis. The floating potential and electron temperature profiles show the existence of a radial inward electric field $\vec{E}_0$; $\vec{E}_0$ increases linearly with the radius in the region of maximum gradient; at 2 kG and $r = 1$ cm, $E_0 = 6$ V/cm. This zero-order electric field creates an $\vec{E}_0 \times \vec{B}_0$ azimuthal rotation of the plasma, with a velocity $\vec{V}_0 = \vec{E}_0\times\vec{B}_0/B_0^2$ in the direction of the electron diamagnetic drift velocity: The waves observed in the laboratory frame will be Doppler shifted by the rotation frequency $F_0 = (1/2\pi r)(E_0/B_0) \simeq 50$ kHz.

In order to compare the characteristics of the observed oscillations with the theory, we solved numerically the linear dispersion relation for electrostatic (since $\beta < m_e/m_i$) collisionless drift waves in a slab geometry.[5] The computation gives the curves with constant growth rate γ in the $\lambda_\parallel, k_y\rho_i$ plane. With the measured macroscopic parameters, but neglecting at first the temperature gradient, the maximum linear growth rate $\gamma \simeq 7\times 10^5\ \text{sec}^{-1} \simeq \omega$ is found for $\lambda_\parallel \simeq 8$ m and $k_y\rho_i \simeq 0.5$. At the maximum value of γ the phase of the perturbed density n_1 leads the phase of the perturbed potential ϕ_1 by 30°. If one adds a temperature gradient equal to the density gradient these results are only slightly modified: The most unstable wavelengths become $\lambda_\parallel \simeq 10$ m and $k_y\rho_i \simeq 0.3$ and the maximum growth rate increases by 50%.[6] At the maximum value of γ, the parallel phase velocity is close to the electron thermal velocity.

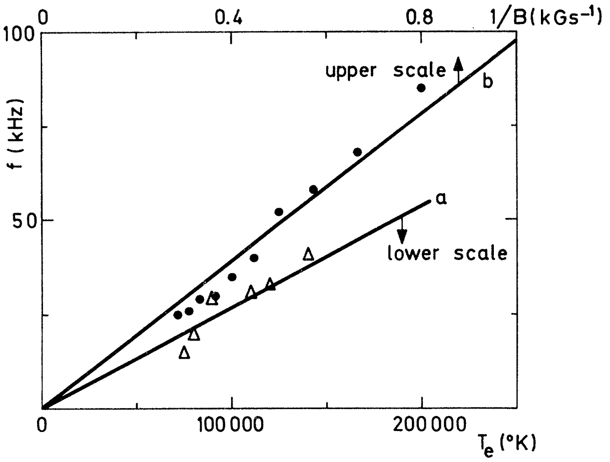

FIG. 2. Parametric variation of the $m = 1$ drift-mode frequency, plotted in the plasma frame. The frequency increases linearly with T_e (curve a) and $1/B$ (curve b).

The frequency spectrum of the ion saturation current exhibits three coherent peaks at 50, 100, and 185 kHz (at 2 kG). From now on, anticipating the results of the measurements given hereafter, we will distinguish the 50-kHz instability as the flute mode and the 100- and 185-kHz instabilities as drift modes. The flute-mode frequency is constant over the explored range of magnetic field values ($1.5 \leq B_0 \leq 3.5$ kG). Over this range the radial electric field E_0 grows linearly with B_0; thus the flute-mode frequency is equal to the plasma rotation frequency: In the plasma frame this instability develops with a zero frequency. The drift-mode frequencies decrease when B_0 increases: Subtracting the Doppler shift due to the plasma rotation yields a $1/B_0$ dependence of these frequencies in the plasma frame. The Doppler-shift corrected frequencies increase linearly with T_e (Fig. 2).

Much work has been devoted to the study of the spatial properties of the waves: radial extension, azimuthal modes, parallel wavelengths. The

Table I. Measured characteristics of the instabilities.

	Flute mode	Drift modes	
Laboratory-frame frequency (kHz), $B_0=2$ kG	50	100	185
Plasma-frame frequency (kHz), $B_0=2$ kG	0	50	85
Azimuthal mode m	1	1	2
Radial extension δ (cm) $\simeq$	1	1	1
Plasma frame azimuthal propagation velocity v_θ (10^5 cm/sec)	0	3.1	2.7
$v_\theta/v_{De} \simeq$		0.7	0.6
$k_y\rho_i$	0.1	0.1	0.2
$k_\perp\rho_i=[k_y{}^2+(\pi/\delta)^2]^{1/2}\rho_i$	0.33	0.33	0.37
Parallel wavelength (m)	$\gg 11$	7-8	7-8
Parallel phase velocity v_φ (10^7 cm/sec)	$\gg 5.5$	3.5-4	6.7
$v_\varphi/\alpha_e \simeq$		0.2	0.3
$\Delta_\varphi=\varphi(n_1)-\varphi(\phi_1)$	180°	10°	10°

radial and azimuthal modes are measured with continuously r- and θ-movable probes. The θ-movable probe can be positioned at the radius of the maximum wave amplitude. It is then continuously moved in the θ direction around the plasma axis. The axis of rotation of the probe mount is moved toward the axis of the plasma column until the zero-order density keeps constant with θ. The drift waves do propagate azimuthally in the direction of the electron-diamagnetic drift velocity in the plasma frame with the characteristics given in Table I.

The parallel wavelengths are measured with several probes aligned along the same magnetic line of force. The alignment is made (1) using a narrow electron beam, and (2) using the radial variation of the floating potential; the different probes are thus positioned on the magnetic line of force to within 1 mm. The phase and amplitude of the instabilities are then measured along the magnetic field, one probe being used as a reference. The measurements (Fig. 3) show that the drift-wave amplitude cancels in the middle of the column and is maximum near the ends whereas the phase shifts by 180° across the middle point; this indicates that the waves are standing in the direction parallel to the magnetic field with a finite wavelength of 7-8 m.

Other results of spatial measurements are presented in Table I. Also shown are the ratio of azimuthal propagation velocity to electron diamagnetic drift velocity, v_θ/v_{De}, and the ratio of parallel phase velocity to electron thermal velocity, v_φ/α_e. The phase difference Δ_φ between n_1 and ϕ_1 has been measured with a Langmuir probe and a capacitive probe located 1 cm apart on the same line of force. All these results are in agreement with the theoretical predictions.

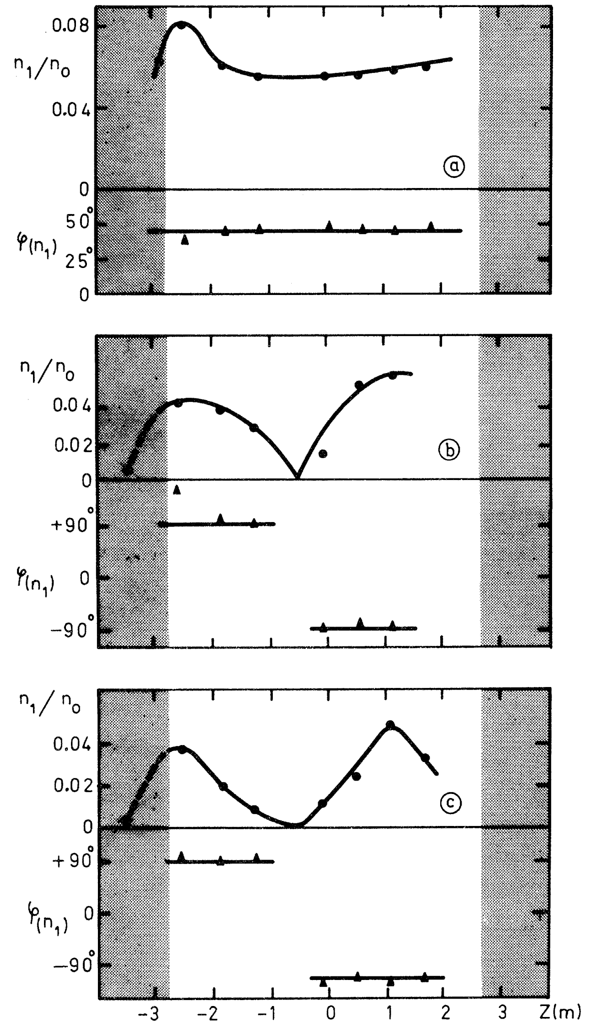

FIG. 3. Parallel wavelength measurements. Experimental conditions: $B_0=2$ kG, $n_0=10^{10}$ cm^{-3}. Phase and amplitude variation of the perturbed density for (a) the flute mode, (b), (c) the drift modes along the plasma column. The reference probe is located at $z=1.8$ m. The shaded areas indicate the regions where the plasma is collision dominated.

We thus get the following picture of the phenomena arising in the plasma: (1) A flute instability driven by the centrifugal force of the $\vec{E}_0\times\vec{B}_0$ rotations grows with zero frequency in the plasma frame. (2) A drift instability is driven by the radial pressure gradient. Identification is supported by the agreement of the measured azimuthal propagation velocities with the theoretical slab-model value (in both magnitude and direction), as well as by the occurence of large but finite parallel wavelengths, evidenced by the zero amplitude at the center of the machine. Use of the measured value of the wavelength yields a computed growth rate close to the maximum theoretical growth rate, if one identifies the radial extension of the mode with a radial wavelength.

Further results concerning the experimental and theoretical aspects of this work will be published elsewhere.

It is a pleasure to thank Dr. J. Tachon who encouraged this study. We also thank P. Blanc, R. Boissier, P. Moyen, M. Occhionorelli, and B. Pando for help in the experimentation.

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Libron Spectra of Oriented Crystals of Paradeuterium and Orthohydrogen in the Ordered State

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New Raman spectra obtained in large oriented crystals of paradeuterium and orthohydrogen give an unambiguous identification of the single-libron modes and remove all former reservations in assigning the $Pa3$ structure to the orientationally ordered phase.

The most direct experimental information concerning the properties of the spin-wavelike excitations called librons in solid hydrogen has been provided by the Raman scattering results.[1,2] However, the extraction of quantitative information has been hampered by the fact that the number of features observed (four or more) was not consistent with the three one-libron modes (E_g, $T_g^{(1)}$, $T_g^{(2)}$) predicted on general grounds for the $Pa3$ structure. A number of possible explanations were proposed. The first was that $Pa3$ was indeed the proper space group for the crystal and the extra features arose from two-libron excitations,[1] but this suffered from the fact that no three lines could be chosen to give simultaneous agreement for the intensities and frequen-