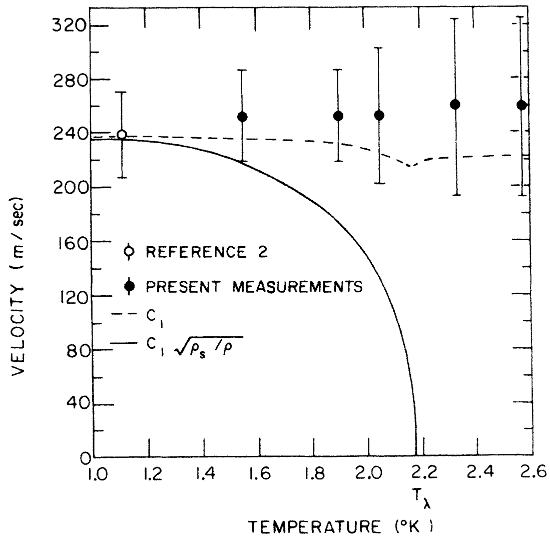

FIG. 2. Phonon velocity calculated from the observed neutron groups compared with the measured velocity of sound and the predictions of reference 1. The vertical bars on the points correspond to the full width at half-maximum of the neutron groups. The instrument resolution is ~ 2°K and is the width observed at temperatures below 1.9°K.

temperature, until temperatures considerably above the lambda point are reached. The width of the neutron group does increase slightly with temperature, however; at 4.2°K the peak is no longer well defined but has become very broad and the maximum in the scattered intensity is at an energy considerably below that corresponding to the velocity of sound. Figure 2 compares the observed phonon velocity as a function of temperature with the measured velocity of sound, c_1, and with $c_1(\rho_s/\rho)^{1/2}$.

The results show clearly that at temperatures up to 2.57°K neutrons scattered with momentum transfer $(p/\hbar)$ of 0.38 Å^{-1} occur in groups whose width increases slowly with temperature and whose energy corresponds to that of a phonon with the velocity of ordinary sound in liquid helium. In the helium-II region there is no apparent dependence on density of the superfluid component. Neither the observed energy change nor the observed width shows any significant change at the λ point such as was observed[2] for neutron scattering from liquid helium at values of $p/\hbar$ near the "roton" region of the dispersion curve. Thus, this region of $\epsilon(p)$ does not depend for its existence upon the fact that the liquid is in its superfluid state.

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EXTERNALLY EXCITED WAVES IN LOW-PRESSURE PLASMA COLUMNS

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This Letter reports measurements on low-frequency waves in hydrogen, neon, argon, and mercury arcs ($f = 4$-400 kc/sec, $p = 0.3$-30 mTorr, longitudinal magnetic field $= 0$ or 10-45 gauss, column diameter $= 5$ or 3 cm). Currents of several amperes were obtained in these gases with a mercury-pool cathode, using a liquid-nitrogen trap in the discharge path.[1] Waves were excited in the positive column by a coil placed 80 cm from the anode and detected by a photomultiplier on the anode side of the coil, as in earlier experiments here on compressional waves in a low-pressure mercury arc.[2-4]

The dispersion curves obtained fall into two groups, those having negative slope (backward waves, Fig. 1) and those having positive slope (forward waves, Fig. 2). Curves obtained by other observers for backward waves in mercury[5] and forward waves in argon[6] and hydrogen[7] are included, together with some of the measurements in mercury reported previously[2]. The symbols specifying the various conditions are explained in Tables I and II.

The backward waves may be described approximately by the empirical relation

$$\omega k = \text{constant}. \qquad (1)$$

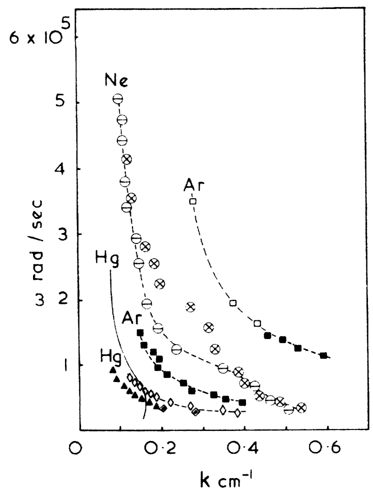

FIG. 1. Backward waves. The symbols represent results in different discharges (see Table I).

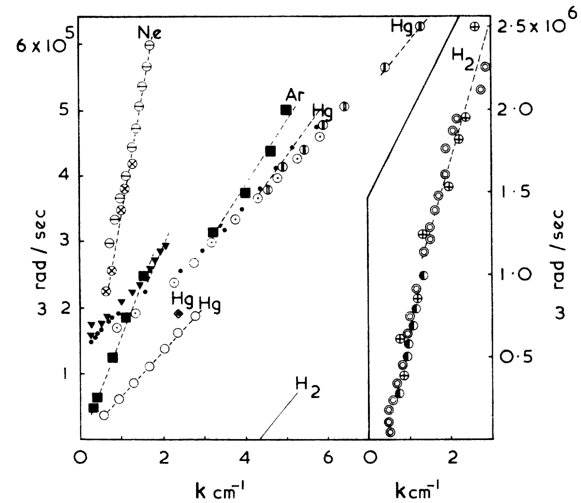

FIG. 2. Forward waves. The meaning of the symbols is given in Table II.

The forward waves are of the form

$$\omega/k = a c_S$$

where $c_S = (kT_e/m_i)^{1/2}$, and $0.4 < \alpha < 1.4$ (see Table II). At low frequencies some of the forward waves exhibit a cutoff in frequency or in wave number. In weak magnetic fields the waves are usually more easily excited: The dispersion curves are not altered by more than 20%, so magnetic fields do not affect the wave propagation critically.

In mercury, at 0.6 mTorr only, both backward and forward waves can be detected. The latter have very small amplitude and appear in a narrow frequency range near $\omega \approx 2\times 10^5$ rad/sec. At higher pressures, only backward waves are observed and at lower pressures, only forward waves. In neon, at 26 and 18 mTorr, we observe both types of wave simultaneously over a wide frequency range at $\omega > 2.5\times 10^5$ rad/sec. The phase and group velocities of the backward waves are much larger than those of the forward waves in this range. There is no evidence of strong coupling (i.e., no observable energy transfer) between these two types of wave. In argon, however, the two backward wave modes are coupled: The short-wavelength mode grows at the expense of the long-wavelength mode at large distances from the exciter.

The attenuation observed varies greatly and in some instances the wave amplitude grows over part of the plasma column. Backward waves in mercury are strongly attenuated; the damping length $\delta \sim 0.5\lambda$. For backward waves in argon and neon the damping is less, $1.5\lambda < \delta < 10\lambda$. Forward waves in neon show alternate regions

Table I. Discharge parameters for backward waves.

Symbol	Gas	T_e (eV)	p (mTorr)	B_z (gauss)	E_z (V/cm)	I_D (A)	N_e (cm^{-3})	Diam	Ref
⊖	Ne	7.0	26	15	0.7	6	0.6×10^{11}	5	
⊗	Ne	7.2	18	15	0.7	6	1	5	
□	Ar		30	15		5.5	5	5	
■	Ar	3.4	14	15	0.7	5	4	5	
◇	Hg	2.5	2-5	0	0.25-0.35	7.5	5	5	
▲	Hg	1.5	2	15	0.25	7.5	5	5	
◈	Hg	2.5	0.6	15	0.1	7.5	2	5	
Solid curve	Hg	2.0	2	0		0.1		2.2	a

[a]See reference 4.

Table II. Discharge parameters for forward waves.

Symbol	Gas	T_e (eV)	p (mTorr)	B_z (gauss)	E_z (V/cm)	I_D (A)	N_e (cm^{-3})	Diam	$a = \omega/kc_s$	Ref
⊖	Ne	7.0	26	15	0.7	6	0.6×10^{11}	5	0.6	
⊗	Ne	7.2	18	15	0.7	6	1	5	0.6	
■	Ar	0.6	40	0	~0	0.01	0.025	~5	0.85(1.4)	b
▼	Hg	5.2	0.4	45	0.1	9		5	0.9	c
○	Hg	2.2	0.4	0	0.1	9		5	0.75	d
●	Hg	3.5	0.4	15	0.1	8	2	5	0.65	
◈	Hg	2.5	0.6	15	0.1	7.5	2	5	0.75	
○	Hg	4.2	0.3	20	0.1	8	0.3	3	0.45	
⊙	Hg		0.4	0		8		5		
Solid curve	H_2		10^3	0		0.13		2		e
◎	H_2	5.4	20	40		2.8		5	0.45	
⊕	H_2	5.4	20	10		4		5	0.45	
◐	H_2	6.1	17	10	1.1	2.5	0.5	5		

[a]Spontaneously generated waves from noise analysis.[3]
[b]See reference 5.
[c]See reference 2.
[d]See reference 3.
[e]See reference 6.

of growth and damping, but on the average, $\delta\sim3\lambda$. In mercury, in the 5-cm tube, the same value of δ applies for forward waves when $\omega<3\times10^5$, but at higher frequencies regions of growth appear and $\delta\sim10\lambda$ overall. In the 3-cm tube $\delta\sim3\lambda$ for these forward waves at $\omega>1.4\times10^5$, and it is the lower frequencies that grow slowly over most of the length observed. Waves in hydrogen show $\delta\sim\lambda$ at the lowest frequencies, and $\delta\sim3\lambda$ when ω is increased to 3×10^5. At $\omega>3\times10^5$, regions of growth and damping again appear and the damping length increases to $\delta\sim10\lambda$ average.

To some extent these waves behave like moving striations. In rare gases a transition from forward to backward waves is seen to occur as the pressure is increased.[8] Measurements on backward waves in argon[9] at high pressure ($p=1$ Torr, $f=650$-1100 cps) are well described by Eq. (1), and the existence of two modes in the argon curves marked □ and ■ may be related to the multiple modes seen at 12 Torr in this gas.[10] We find no backward waves at all in hydrogen; this is consistent with the fact that striations in hydrogen and some other molecular gases are forward waves.[11]

At higher pressures these moving striations which are backward waves have been interpreted as ionization waves.[12] Observations on backward waves at low pressures, near 1 mTorr, have not been explained.[5,13] It is probable that the waves of Fig. 1 are ionization waves, but they are externally excited small-amplitude waves in a stable regime of the discharge, in contrast to the naturally occurring large-amplitude waves arising in oscillatory regimes. (Small pulsed perturbations have been studied in a stable regime by Pekárek[14] and, recently, in a quasistable regime by Cooper.[15]

The forward waves of Fig. 2 have velocities near the Tonks-Langmuir electroacoustic wave velocity c_S[16]; with one exception their velocity is below c_S. The ion-neutral collision frequency is greater than the wave frequency in most instances, so $\omega/k<c_S$ is to be expected.[8] The waves are probably electroacoustic in nature, though modified by ionization processes and ion-neutral collisions. The exceptionally high wave velocity in argon at low frequencies[6] may be partly accounted for if $\gamma>1$ should be included in c_S.

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