affect the symmetry of the transition. The observation that within our errors universality and scaling are obeyed in He II may be compared with the previously observed *departures* from scaling and universality in the ratio A_0/A_0' of the amplitudes of

$$C_p = -A_0 \ln|\epsilon| + B_0 \qquad (12)$$

above and below T_λ. Experiments yield $A_0/A_0' > 1$ and dependent upon P. Scaling requires $A_0/A_0' = 1$, and from universality we expect A_0/A_0' to be independent of P. Our present results strengthen our previous belief[2,3] that the source of departures from universality and scaling near T_λ must be found by examining the high-temperature phase.

We have demonstrated in this paper that the superfluid density cannot be described by a pure power law. When we invoke higher-order singular contributions of a reasonable functional form to ρ_s/ρ, we can obtain agreement with scaling and universality within our permitted errors.

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Energy Loss of a Low-Energy Ion Beam in Passage through an Equilibrium Cesium Plasma*

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The energy loss of a beam of cesium ions traversing a near-thermal equilibrium cesium plasma has been measured as a function of plasma density at ion-beam energies of 35 to 150 eV. The plasma electron/ion temperature was 2100°K, and the charged-particle density was varied from $(0.1 \text{ to } 3.7)\times 10^{11}$ cm^{-3}. The measured energy loss is found to agree very well with theoretical predictions.

Despite the fact that a large amount of theoretiwork[1-10] has been devoted to the problem of the energy interchange of a charged test particle with a plasma, there has been little experimental work performed. This is, of course, largely attributable to the experimental difficulties involved, including the relatively small amount of energy loss, complications produced by the confining fields, spatial inhomogeneities in the plasma, and the difficulty of relating experimental results involving non-Maxwellian plasmas to theories which usually assume a Maxwellian distribution for the plasma constituents.

In this Letter, we report measurements[11] of the average energy loss of a low-density, low-energy beam of cesium ions in passage through a low-density cesium plasma. In order to allow comparison with theory, the cesium plasma source was designed so that the conditions in the plasma are as close as possible to those generally assumed in the theory. That is, the plasma contains no imposed electric or magnetic fields, and minimal thermal and density gradients result in a near-thermal equilibrium homogeneous plasma.

In the only previous experimental work, Ormrod[12] has reported passing a 10–70-keV proton beam and a 10–70-keV deuteron ion beam through an argon plasma produced by an arc discharge, and Halverson[13] has injected a 5-keV proton beam into a lithium arc discharge plasma. These experiments were carried out using experimental parameters (e.g., nonequilibrium plasmas with strong magnetic fields present) which cannot at present be incorporated into theoretical estimates with any significant degree of accuracy, and indicated an energy loss roughly one third to one half that predicted by the theory. The present measurements, on the other hand, carried out under conditions which apply directly to the extensive calculations available in the literature, are found to agree with theory within the experimental uncertainty.

Many of the theoretical calculations of energy-loss rate (dE/dt) have been based upon the Fokker-Planck type of equation discussed by Chandrasekhar[2] and generalized by Rosenbluth, MacDonald, and Judd.[3] In these theories, divergences due to neglect of cooperative screening and plasma wave effects at large separations, or due to inadequate treatment of the dynamics of close encounters, are eliminated by the introduction of cutoffs at the Debye length and/or at the distance of closest approach.

On the other hand, the more rigorous unified or convergent theories,[5-10] which make use of the plasma kinetic equations, eliminate the need for any phenomenological cutoffs. Generally, the convergent theories have not included a tractable expression for the energy loss rate of a slow test ion, moving faster than the plasma ions but slower than the plasma electrons, as is the case in our measurements. An exception is the treatment described in a series of papers[5-9] by Aono and co-workers. In the case of a test ion of mass M, velocity V, and charge q, traversing an infinite homogeneous plasma at temperature T and density n_s, the energy-loss rate of the particle is given by[7]

$$-\frac{dE}{dt}=4\pi q^2\sum_{s=1}^{2}\frac{n_s e_s^2}{m_s v_s}\left[F_s\left(\frac{V}{v_s}\right)\ln\left(\frac{4\mu_s kT\lambda_s}{\pi\gamma|e_s q|n_s}\right)+G\left(\frac{V}{v_s}\right)\right], \tag{1}$$

where

$$F_s(u)=\frac{2}{\sqrt{\pi}}\left[\int_0^1\exp(-u^2x^2)\,dx-\left(1+\frac{m_s}{M}\right)\exp(-u^2)\right].$$

An expression equivalent to Eq. (1) has also been given by Perkins.[10] The subscripts label the plasma constituents, cesium ions and electrons for our case. The plasma particle mass is m_s, the charge of the plasma particle is e_s, the plasma particle thermal speed is $v_s=(2kT/m_s)^{1/2}$, the reduced mass is $\mu_s=m_sM/(m_s+M)$, the Debye length is $\lambda_s=(kT/4\pi m_s e_s)^{1/2}$, k is Boltzmann's constant, and $\ln\gamma=0.577\cdots$ is Euler's constant. $G(V/v_s)$ represents the dependence of the Coulomb logarithm on the velocity of the test particle, and has been evaluated numerically by Itikawa and Aono.[7] Equation (1) reduces to the expression given by Butler and Buckingham,[4] except for differences in the Coulomb logarithm, and can be evaluated to give the contribution to the energy-loss rate from both plasma ions and plasma electrons. The plasma ions are found to contribute significantly to the energy-loss rate only when the beam is moving extremely slowly.

At our range of beam energies (35–150 eV) the beam speeds, although only a fraction of the plasma electron speeds, are sufficiently high so that the energy loss is due primarily to the interaction of the beam ions with the plasma electrons.

Our plasma source is shown in Fig. 1. It consists of a capped tantalum foil cylinder, 7.5 cm long and 2 cm in diameter, surrounded by a concentric heating element and appropriate heat shields. Small holes in the end caps allow the beam to pass through the plasma along the axis of the cylinder. The heating element, used to radiatively heat the plasma cylinder, is made from two coaxial tungsten cylinders joined at

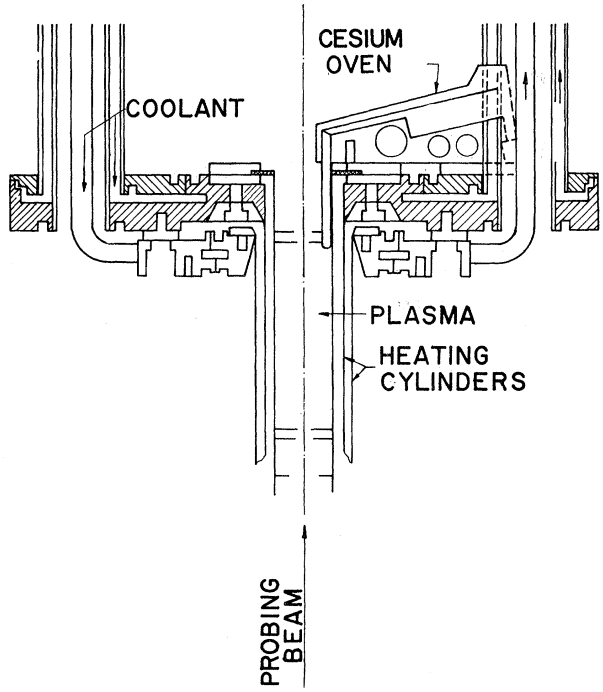

FIG. 1. A schematic diagram of the plasma source.

TABLE I. Plasma parameters at typical operating conditions.

Plasma temperature	2100°K
Ion/electron density	3×10^{11} cm^{-3}
Atom density	7.5×10^{11} atoms/cm^3
Fractional ionization $[n_p/(n_p+n_a)]$	0.29
Debye length	5.8×10^{-4} cm
Number of particles in a Debye sphere	480

the bottom. This configuration reduces the magnetic field from the large heating current (up to 300 A) to a negligible value in the plasma cylinder. The plasma cylinder is insulated from the heating element and the cesium oven by ceramic disks, and is maintained at ground potential. To minimize magnetic fields caused by the external circuit, the heating current is fed symmetrically from two coaxial lines and the currents in these lines are carefully balanced. The plasma cylinder can be radiatively heated to a maximum temperature of about 2500°K.

The cesium oven is equipped with heater, cooling coil, and temperature sensors enabling independent control of the cesium vapor pressure and is connected to the plasma cylinder by means of a short tantalum tube as shown in Fig. 1. In general, when cesium atoms or ions strike a hot surface such as the wall of the tantalum cylinder, they are adsorbed for a short time in a surface layer and then a fraction are re-emitted as ions in thermal equilibrium with the wall. At our normal operating conditions, this fraction is quite large (>0.5). The ions together with the electrons emitted from the walls by thermionic emission form a plasma whose constituents are in near-thermal equilibrium with each other and with their container. Obviously, the wall collisions are dominant in establishing the near-thermal equilibrium character of our low-density plasma.

An optical pyrometer is used to measure the plasma temperature T, using a small hole in the side of the plasma cylinder as a black-body radiator. In addition, the neutral-atom flux effusing from this same hole is measured with a surface ionization detector. The neutral-atom flux can be directly related to the neutral-atom density n_a inside the plasma cylinder through kinetic theory and simple geometrical considerations. The ion/electron densities, n_p and n_a, respectively, assumed to be equal, are then calculated from the Saha equation. Table I lists typical values for the parameter which characterize our plasma at the operating conditions.

The cesium ion beam is produced by extracting ions from a commercial thermionic ion source[14] and a Soa immersion lens. It is electrostatically focused. The axis of the ion source is offset from the axis of the plasma cylinder in order to prevent neutral atoms which have diffused out of the plasma cylinder from hitting the hot cathode, ionizing, and becoming part of the beam. Several sets of deflection plates, directly before and after the plasma cylinder, can be used if necessary to trim the direction of the ion beam. After passing through the plasma, a Faraday cup and a retarding potential analyzer are used to detect and energy analyze the ion beam. The detector has an angular acceptance angle of 1.5 deg. Typical operating conditions for the ion gun are shown in Table II.

Note that the average separation between the beam ions is many Debye lengths so that each beam ion while in the plasma interacts individually with the plasma, being almost completely shielded from the influence of other beam ions. Surrounding the entire apparatus is a partially magnetically shielded vacuum chamber capable of maintaining a pressure of about 4×10^{-7} Torr when the plasma cylinder is heated to 2500°K.

TABLE II. Cs^+ beam parameters.

Energy	50 eV
Energy spread (FWHM)	0.8 eV
Current	1×10^{-10} A
Beam density	3.7×10^{4} ions/cm^3
Average particle separation	0.03 cm
Approximate beam diameter	0.15 cm
Beam path length in plasma	7.5 cm

The experimental energy loss ΔE is determined in the following manner. At a given plasma density, plasma temperature, and ion beam energy, the ion beam current (I) is recorded as a function of applied retarding voltage (V) in a multichannel analyzer. The I-V curve is then differentiated by a digital computer. From this analysis, beam parameters such as the full width at half-maximum and the peak energy of the distribution are obtained. These values are referenced to values obtained at the same settings of plasma temperature and beam energy, but with cesium oven cold (i.e., "zero" density). The difference between the peak of the energy distribution at "zero" density and the peak of the energy distribution at a particular density is taken to be the reported energy loss ΔE.

To relate ΔE to Itikawa and Aono's[7] expression for the energy loss rate dE/dt, the theoretical expression is multiplied by Δt, the transit time of the ion in passage through plasma. Δt is set equal to L/V, where L is the length of the plasma and V is the speed of the beam ion. This is a good approximation when the magnitude of the energy loss is small compared to the beam energy (i.e., $\Delta E/E \ll 1$). Both theory and experiment give values of $\Delta E/E$ which are substantially smaller than unity, supporting this approximation.

The energy loss of a 50-eV cesium ion beam is plotted as a function of density at a plasma temperature of 2100°K in Fig. 2. The uncertainty in the magnitude of the energy loss is ± 0.050 eV. The uncertainty in the ion/electron density is estimated to be $\pm 2\times10^{+10}$ particles/cm^3. Each datum point in the figure represents the differentiation of an I-V curve, which consists of approximately 300 current and voltage points each, taken in about 30 sec using the multichannel analyzer. One run typically consisted of two I-V curves at each of several different densities and at each of three different beam energies. This required on the order of 24 to 36 h per run primarily because about 30 min were required for the density to stabilize at each new setting. The points in Fig. 2 represent the 50-eV points taken on three separate runs. The spread of data points as shown is attributable largely to statistics resulting from the low ion beam current levels, small energy loss, and relatively coarse voltage scans (each channel of the multichannel analyzer represented 20 mV).

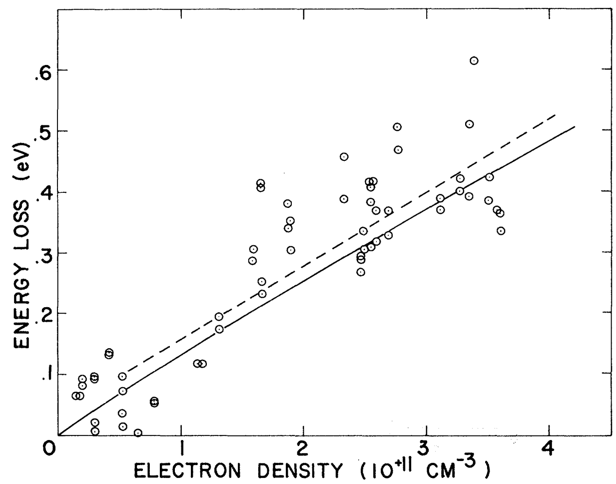

FIG. 2. Experimental energy loss plotted as a function of plasma density, for a 50-eV ion beam and a plasma temperature of 2100°K. Solid curve, theoretical prediction of Itikawa and Aono; circles, present experimental results; dashed line, least-squares fit of these points by a straight line.

These results, the first to examine the density dependence of the energy loss, show surprisingly good agreement with the theory despite the relatively large scatter of the individual data points. An energy loss of one third to one half that predicted by theory as seen in other experiments[12,13] is not observed. Although we present data only at 50 eV, other data taken at ion beam energies of 35 and 150 eV and a plasma temperature of 2100°K are also in reasonable agreement with theoretical predictions.

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Direct Photoelectric Measurement of the Interface-State Density at a Pt-Si Interface

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From infrared photoelectric measurements, we have obtained a density of the interface states lying between 0.745 and 0.825 eV from the silicon conduction band at a Pt-Si interface. We show the following: The transitions occur preponderantly from a level ~0.3 eV below the platinum Fermi level; a peak exists in the interface-state density at 0.79 eV from the silicon conduction band; and the pseudo Fermi level in the semiconductor moves up with forward bias.

In this communication we present the first direct experimental evidence, to our knowledge, of the existence of interfacial states in the band gap of silicon by photoemission. Some of these interfacial states were qualitatively predicted by Heine[1] on the basis of electron-wave-function matching at either side of a metal-semiconductor interface. The existence of interface states was first demonstrated by Bardeen[2] from interface pinning of the Fermi level for metals of different work function, and then the location of a peak in the interface-state density of a Au-Si diode was estimated by Crowell and Roberts[3] from capacitive measurements. For our investigation, we have used a Pt-Si interface so as to photoinject electrons from platinum to silicon. A spectral analysis of the photocurrent I as a function of $h\nu$ for low-energy photons (<0.8 eV) reveals the existence of interface states in the band gap of semiconductor.

Slices of Si (111) (n type, 10 Ω cm) were mechanically and chemically polished, then rinsed in hydrofluoric acid before platinum evaporation in ultrahigh vacuum ($<10^{-9}$ Torr). The Ohmic contacts were made with gallium, and the ensemble showed the usual Schottky diode caracteristic of current and capacitance as a function of voltage. In the same mechanical assembly we obtained the photoemission using a modified Beckman DK 2A spectrophotometer with a tungsten-lamp source, that was calibrated with a Schwartz thermopile. The incident light traversed the silicon before hitting the silicon-platinum interface. The photocurrent measurement was done at 400 Hz by synchronous detection with a low-impedance preamplifier, while a continuous bias voltage was maintained by a battery.

From the photoelectric yield of electrons per photon as a function of $h\nu$, as well as measurement of capacitance in reverse bias, we determine the potential barrier $\psi_B = 0.91 \pm 0.05$ eV, in agreement with values already published in the literature.[4] At lower photon energy, we observe a supplementary electron excitation, of the order of 10^{-11} to 10^{-13} A. The mode of detection rules out any spurious effects arising from the geometry or polarization. The disappearance of the photocurrent in the absence of illumination while the mechanical chopper is on, rules out the existence of induction currents or any vibration-modulated currents. This excitation, we shall argue below, can be unambiguously attributed to interface states. If one normalizes the photoelectric yield curve (forward bias decreasing the interface electric field gives a lower collection efficiency) and plots it as a function of $h\nu$, one obtains a typical normalized yield, $Y(h\nu, V)$, shown in Fig. 1 (at 300°K). The beginning (not