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Experimental Studies of the Bohm Criterion in a Two-Ion-Species Plasma Using Laser-Induced Fluorescence

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The Bohm criterion is studied experimentally in the case of a two ion species plasma. Measurements are carried out in Ar and Ar + He plasmas ($P_{\mathrm{Ar\,I}} \sim 0.1$ mtorr, $0 \leq P_{\mathrm{He}}/P_{\mathrm{Ar}} \leq 25$, and $0 \leq n^+_{\mathrm{He}}/n_e \leq 0.5$, $T_e \leq 2$ eV) created in an unmagnetized dc hot filament discharge confined by surface multidipole magnetic fields. Laser-induced fluorescence (LIF) measurements of Ar II ion velocity distribution functions (ivdfs) within the presheath up to the sheath edge show that the ions reach the sheath edge traveling faster than their individual Bohm speed by more than 75%, approaching a speed equal to the ion sound speed of the system.

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The flow of multiple ion species onto plasma boundaries is an important feature of many plasma systems. Divertors and limiters in fusion plasma devices, etching and deposition plasmas, and Langmuir probes are among the many examples where the plasma-wall interaction is a salient feature of the system and in which multiple ion species are often present. Understanding sheath formation in such plasmas, a longstanding problem, remains an unsolved fundamental and practical problem in plasma science. It is a topic that has only recently begun to attract interest [1–4].

Langmuir was the first to envision the problem of sheath formation in terms of two distinctly different scale lengths. He recognized that ions must arrive at the sheath edge with some velocity derived from weak electric fields extending from the sheath edge some "considerable distance" [5] into the plasma compared with the sheath thickness. The region of this long scale length, λ_p, is now known as the plasma presheath [6–8], and the sheath scale length is the Debye length, λ_D. Bohm [9] was the first to derive an expression for the minimum mean kinetic energy required of the ions at the sheath edge of a single species plasma in order for real sheath solutions to exist ($mv^2/2 \geq T_e/2$), where v is a fluid velocity and T_e is measured in eV. These along with others have pointed out the discontinuity in the asymptotic forms of the electric field of the sheath and presheath where they join, and have derived expressions for an electric field in the transition region. Electric field strengths and thicknesses of this transition region have now been measured [10] in weakly collisional plasma for which the ion-neutral collision length, λ_{in} is much larger than λ_D, and much smaller than the system length, L_s; i.e., $\lambda_D \ll \lambda_{\mathrm{in}} \ll L_s$. These results provide experimental justification for each of the three scale lengths: sheath, transition, and presheath.

Riemann and others [1–3] have argued that for weakly collisional plasmas, individual ion species in a multiple ion species plasma must satisfy a generalized Bohm criterion expressed as

$$1 \geq \sum_j \frac{(n_{j0}/n_{e0})C_j^2}{v_j^2}, \tag{1}$$

where the ion sound speed for each species is $C_j = \sqrt{T_e/m_j}$, m_j is the ion mass, and j numbers the ion species. The zero subscript refers to quantities at the boundary between the sheath and presheath. Unlike the case of a single species plasma where the equality is normally satisfied by the ion species reaching its sound speed, in the case of multiple ion species, the equality may be satisfied by speeds faster or slower than the sound speed for a given ion species. Two simple solutions satisfying Eq. (1) are that all ions attain the same speed at the sheath edge, and that each species attains its own Bohm speed. The former solution works out to be the ion acoustic speed of a homogeneous plasma of multiple ion species with no ion drifts. Many authors quite naturally have assumed the latter solution [11].

Recently, Franklin pointed out that for the case of spatially uniform ionization and energy conserving flow, all the ion groups come out at their own Bohm speeds [3]. Most plasma used in practical applications of course have as a minimum significant ion-neutral collisions. If the neutral pressure is sufficiently high, the flow is mobility limited. In this case, Franklin [4] among others have shown that the ratio of ion flow velocities at the sheath edge is that of their mobilities. This ratio will not in general equal unity, nor will it equal the ratio of their Bohm speeds, thus eliminating the two simplest solutions cited above. However, preliminary experimental results by Hala [12], based on ion acoustic wave measurements suggest that Ar II ions reach the same speed as He II ions near the sheath edge. This Letter is the first to present experimental evidence that one of the ions in a two species plasma reaches the sheath edge traveling much faster than its own Bohm speed.

The experiments reported here were performed in a dc hot filament multidipole plasma system [13] described in detail by Hala [14]. Helium was added to a low pressure Argon discharge (at a neutral pressure of approximately 0.1 mtorr). The ion concentrations in the bulk plasma, far from the sheath, were determined from the measured ion acoustic wave phase velocity, which can be shown, in the case of a two ion species plasma for which ion drifts are negligible, to reduce to a concentration weighted average of the sound speeds of the ion constituents [14],

$$v_{\mathrm{ph}} = \sqrt{(n_1/n_e)\mathrm{C}_1^2 + (n_2/n_e)C_2^2}, \tag{2}$$

where 1 and 2 refer to Ar II and He II ions, respectively. Assuming charge neutrality, the measured phase velocity yielded the ratio of each concentration to the electron density. At a total neutral pressure of 2.65 mtorr under these conditions, the ratios $P_{\mathrm{He}}/P_{\mathrm{Ar}} \geq 26$, and $n_1/n_e \geq 0.65$. Although the ion concentration ratio is nearly unity, the neutral pressure ratio is large, primarily because of Penning ionization of Ar by He*. We estimate that the resonant charge exchange mean free path for Ar is larger than that of He, by a factor of approximately 3.5, and that the mean free path for Ar ion charge exchange on He I is larger than that of resonant charge exchange for He by a factor of 7 [15].

The location of the sheath edge was determined by plasma potential measurements made with an emissive probe, analyzed using the inflection point method in the limit of zero emission [16]. The heated filament was approximately 5 mm in length, 0.025 cm in diameter, and was oriented so that its axis was parallel to the boundary plate. Langmuir probes were used to measure the electron temperature in the bulk plasma and revealed that there were two Maxwellian electron components, nominally 1.0 and 4.5 eV, respectively. The effective electron temperature used for sound speed calculations was the harmonic mean of the two temperatures [17]:

$$T_e = \frac{1}{(n_{ec}/n_e)/T_{ec} + (n_{eh}/n_e)/T_{eh}}, \tag{3}$$

where n_{ec} and n_{eh} refer to the cold and hot electron densities.

Argon ion flow through the bulk plasma into the presheath and sheath was measured using a diode laser based [18] laser-induced fluorescence diagnostic described elsewhere [19]. The sheath was created at the focus of the collection optics using a stainless steel plate mounted on a stalk that could be moved axially along the direction of the laser beam. The beam direction defined $-\mathbf{z}$ direction. The location of the fluorescence collection optics remained fixed. The atomic energy level terms used for laser-induced excitation ($^4F_{7/2} - {}^4D^0_{5/2}$), and fluorescence ($^4D^0_{5/2} - {}^4P_{3/2}$) correspond to (air) wavelengths of 668.4293 and 442.6001 nm, respectively, for ions at rest in the laboratory frame. The intersection of the focus of the collection optics and the laser beam created an approximately cylindrical diagnosed volume of about 15 mm^3, which subtended a small solid angle at objective of the collection optics 34 cm away, about 4.5×10^{-2} sr. A pinhole of 1 mm diam placed at the focal plane of the objective lens created a spatial resolution which, since the magnification there was about 0.7, created a spatial resolution of about 1.5 mm. The PMT collected the fluorescence through an interference filter centered at 442.6 nm (FWHM = 0.1 nm), with a transmission coefficient on line center of 50%. A lock-in amplifier and mechanical chopper (spun at 3 kHz) were used to discriminate signal from noise.

The LIF signal is proportional to the reduced one-dimensional ion velocity distribution function (ivdf) along the beam direction, $f(v_z, z)$. Standard references [19] to the meaning of the LIF signal describe the integration along the velocity space coordinates normal to the beam direction. The LIF signal was obtained as a function of detuning frequency by directing the laser beam through an iodine gas cell before allowing it to pass through the plasma, so that I_2 and Ar II fluorescence signals could be obtained simultaneously. The frequency of the I_2 fluorescence corresponding to an Ar II ion was used as the fiducial mark from which detuning frequencies were calculated. This point on the iodine spectrum was identified with the help of the standard I_2 atlas [20]. The shape of the LIF signal was converted to velocity dependence using the first order Doppler shift, $v_z = \lambda(f - f_0)$.

The axial boundary plate immersed within the plasma was biased negatively with respect the metal vacuum chamber wall by over $20T_e$. Emissive probe measurements revealed the gross structure of the plasma potential in the plasma: a long region of weak potential gradient leading up to a rapid drop in potential near the plate. Measurements of the ivdfs at various locations in this potential structure are shown in Fig. 1. Far from the transition from presheath to sheath, the Doppler shifts are small and the shape of the distribution is asymmetric, distended on the low velocity side toward $v = 0$. This feature of the ivdf is expected whenever charge exchange collisions create low velocity ions from the distribution of nondrifting neutrals of the same element. The flow velocity of the ions rises as they near the plate, and the peak of the ivdf achieves a value of the Bohm speed, $C_s = 2.07$ km/sec at a distance of 6 mm from the plate. Closer to the plate, we begin to observe a change in the shape of the distribution: it becomes symmetric again and then becomes distended markedly on the high velocity side. Similar behavior, which has been observed by other investigators [21], signals the presence of very fast ions in the sheath. The strength of the potential gradient here in the sheath relative to the presheath, along with the finite size of the diagnosed volume produce a relatively broad, distended ivdf. Closer to the plate we reach a point at which we can no longer detect any signal at all. Two

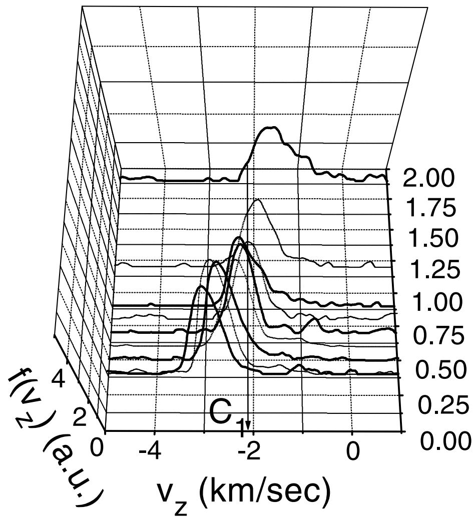

FIG. 1. A family of ivdfs for the pure Ar plasma case show. The rms velocity crosses c_1 at the sheath edge.

factors determine this. The ion density is diminishing within the sheath, and the solid angle subtended by the objective lens begins to be cut off by the plate itself. We could not detect any signal for $z < 3$ mm.

The position of the sheath edge is indicated by the radical change in the slope of the plasma potential between the sheath and presheath regions. The profile near the plate is shown in Fig. 2. The sheath edge determined in this way is found to be at $z = 6.0 \pm 0.5$ mm. The position of the sheath edge relative to the plate may be estimated from the Child-Langmuir model: $d_{\mathrm{CL}} = 2^{5/4}\lambda_{Do}(e\Phi_w/T_e)^{3/4}/3$, where Φ_w is the potential difference between the boundary plate and the sheath edge and d_{CL} is the Child-Langmuir sheath thickness. For this case, $d_{\mathrm{CL}} = 6.2 \pm 0.6$ mm, where we have estimated the uncertainty to be approximately 10%. The agreement is surprisingly good given that the Child-Langmuir model assumes a pure ion sheath and neglects both the finite value of the electric field and the finite velocity (the Bohm velocity) of the ions at the sheath edge. But these omissions create errors with opposite effects. The square velocity moment of the ivdfs was calculated and the rms speed was compared with the Argon ion sound speed, or Bohm speed. The percentage by which $\sqrt{\langle v^2 \rangle}$ differed from C_1 was calculated for each ivdf and graphed as a function of position in Fig. 2, along with the plasma potential profile. Within the 5% uncertainty of our rms velocity determination, and the rms velocity passes through the Bohm velocity at the sheath edge, as expected by the Bohm Criterion for single ion species plasma.

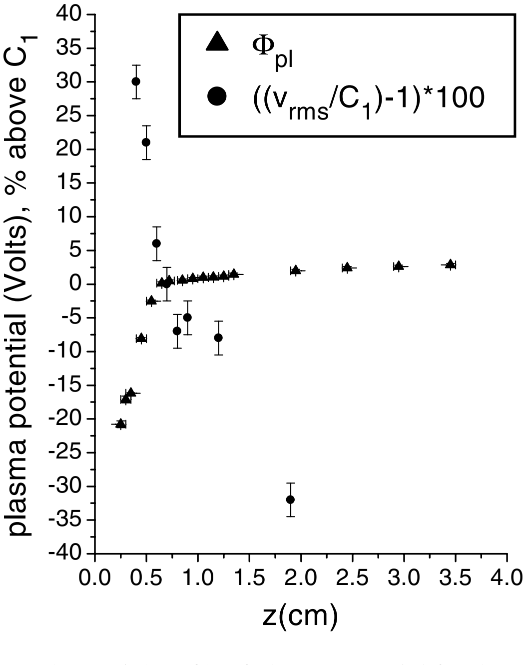

FIG. 2. The spatial profile of plasma potential for the pure Ar plasma shows the presheath and the sheath. At the location of the sheath edge, within error, the rms velocity passes through the Bohm speed.

For the He-Ar plasmas of this experiment, Langmuir probe measurements revealed a bi-Maxwellian electron temperature, with cold and hot components of 0.97 and 4.68 eV, respectively. The effective electron temperature was used to calculate the Bohm speed for each species, of 1.62 and 5.12 km/sec for Ar II and He II ions, respectively. The plasma density in the bulk plasma remote from the walls of the chamber and remote from the plate, was approximately 1×10^9 cm^{-3}, giving a Debye length of approximately 0.25 mm. A typical ion acoustic velocity in the bulk plasma far from the plate was $v_{\mathrm{ph}} = 3.28$ km/sec, giving relative ion concentrations: $n_{\mathrm{Ar}}/n_e = 0.66$ and $n_{\mathrm{He}}/n_e = 0.34$. A family of ivdfs is given in Fig. 3. The ivdfs in Ar-He plasma are noisier than the case of the pure Ar plasma. However, it is clear that

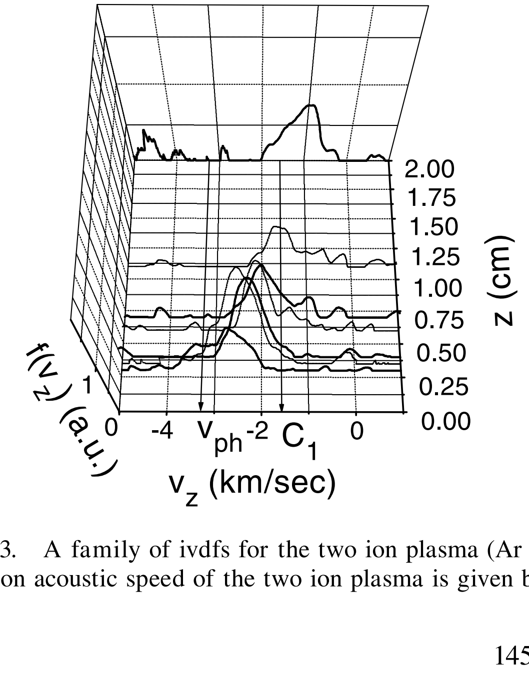

FIG. 3. A family of ivdfs for the two ion plasma (Ar + He). The ion acoustic speed of the two ion plasma is given by v_{ph}.

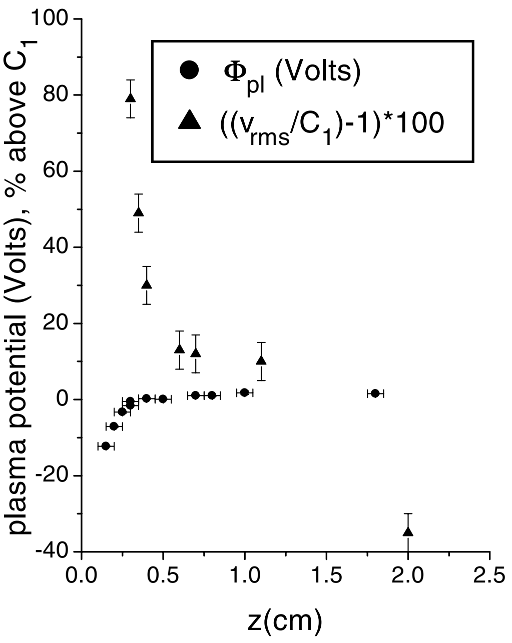

FIG. 4. The plasma potential profile for the Ar + He plasma reveals that the rms velocity of the Ar II ions is well beyond the individual Bohm speed c_1 and approaching the ion sound speed of the system (as measured in the bulk) at the sheath edge.

for $z < 1$ cm, the peak of the distribution exceeds the Ar II Bohm speed. The asymmetry on the $v_z = 0$ side of the ivdfs is present as was the case for the pure Ar plasma. Beyond the sheath edge, we observed ivdfs that became distended on the high velocity side of the peak of the distribution.

The Ar II Bohm velocity was compared with $v_{\rm rms}$ as a function of position relative to the plate, and is shown in Fig. 4. Emissive probe measurements show that the sheath edge, z_o is $3.0\ \text{mm} \le z_o \le 4.0$ mm, and the calculation of $d_{\rm CL} = 2.5 \pm 0.3$ mm. LIF measurements clearly show that the rms speed of the Ar II ions exceeds its own Bohm speed. We point out that ion sound speed of the system ($v_{\rm ph} = 3.28$ km/sec) itself of course is much faster than the Ar II Bohm speed (103% greater than c_1). At the sheath edge, the rms velocity is 77% that of the Ar II Bohm speed, and rapidly approaches the ion sound speed of the system. It is hard to escape the conclusion that Ar II ions fall into the sheath moving significantly faster in the Ar-He plasma than they do in the pure Ar plasma. This is the principal result of this Letter.

In summary, our data show that for the case of two positive ion species plasma, Ar *II* + He *II*, for a finite small value of λ_D/λ_{io}, Ar II ions reach the sheath edge traveling significantly faster than their individual Bohm speed. The speed they attain at the sheath edge in a pure Ar plasma of comparable neutral Ar pressure agrees with the single species Bohm velocity. The Ar II ions approach the sound speed of the system, as calculated in the bulk of the mulitiple ion species plasma.

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