Experimental Test of Instability-Enhanced Collisional Friction for Determining Ion Loss in Two Ion Species Plasmas

Chi-Shung Yip and Noah Hershkowitz*

Department of Engineering Physics, University of Wisconsin, Madison, Madison, Wisconsin 53706, USA

Greg Severn†

Department of Physics, University of San Diego, San Diego, California 92110, USA

(Received 8 April 2010; published 2 June 2010)

Recent experiments have shown that ions in weakly collisional plasmas containing two ion species of comparable densities nearly reach a common velocity at the sheath edge. A new theory suggests that collisional friction between the two ion species enhanced by two stream instability reduces the drift velocity of each ion species relative to each other near the sheath edge and finds that the difference in velocities at the sheath edge depends on the relative concentrations of the species. It is small when the concentrations are comparable and is large, with each species reaching its own Bohm velocity, when the relative concentration differences are large. To test these findings, ion drift velocities were measured with laser-induced fluorescence in argon-xenon plasmas. We show that the predictions are in excellent agreement with the first experimental tests of the new model.

DOI: 10.1103/PhysRevLett.104.225003 PACS numbers: 52.40.Kh, 52.27.Cm, 52.35.−g, 52.40.Hf

Plasma sheaths are characteristic of all bounded plasmas. They are plasma potential barriers that form to provide a balance of electron and ion fluxes to boundaries. Their characteristics are critical to the operation of all devices which depend on plasmas. Examples range from light sources to materials processing plasmas [1] to fusion plasmas [2] as well as objects encountered in space physics. Langmuir [3] and Bohm [4] predicted that the ions in single ion species plasmas are supersonic at the sheath edge where their drift velocity is given by $v = c_s = \sqrt{T_e/m_i}$, where T_e is the electron temperature and m_i is the ion mass. This requirement is now called the Bohm criterion.

The Bohm criterion has been generally accepted as being valid for plasmas with single ion species. Experiments have employed laser-induced fluorescence (LIF) to directly measure ion drift velocities near boundaries in dc [5] and rf plasmas [6] and have verified the Bohm criterion in single species plasma. LIF has proved capable of diagnosing a variety of boundary conditions including plasma thermodynamics in rf plasmas, [7] spatial nonuniformities in sheaths formed at heterogeneous conducting boundaries [8], and two dimensional velocity profiles in a helicon source [9].

The Bohm criterion has been generalized [10] for the case of multiple positive ion species plasma to give a condition $1 \geq \sum_i (n_{i0} c_j^2)/(n_{e0} v_{i0}^2)$, when $T_i \ll T_e$, and where the nought refers the speeds to the sheath edge. This is one condition with as many variables as the number of ion species. For the case of two ions, this condition admits of a continuum of solutions in which either ion may have an arbitrarily large speed at the sheath edge so long as the other ion is a fraction of its own Bohm speed. There are two particularly simple intermediate solutions: every ion species of ion reaching the sheath edge at its own Bohm velocity, and all ions reaching the leaving sheath edge at the system sound velocity $c_s = \{\sum_i [c_{s,1}^2 (n_{i0}/n_{e0})]\}^{1/2}$ at the sheath edge. Most investigators have assumed the former solution, that the Bohm criterion applies to each ion species in a plasma separately and theoretical studies have demonstrated this result under collisionless and weakly collisional conditions [11]. Recent experiments on plasmas containing two positive ion species with comparable ion concentrations, however, found results closer to the latter solution (see Ref. [12] and references therein).

The process of sheath formation in two species plasmas also involves streaming ions which results in streaming instabilities. Experimental evidence of such instabilities has been reported [13]. However, they were thought to be insignificant in determining the ion velocities at sheath edge as their amplitudes were very small. Recently, Baalrud *et al.* [14] theoretically determined the solution to the Bohm criterion in a multispecies plasma by including the effects through the application of instability-enhanced friction between the ion species. In their prediction, the difference between the drift velocities of the ion species at the sheath edge is nonzero, and depends on the difference in ion concentrations. They showed that when the ion concentrations are comparable in a two ion species plasma, each ion species reaches the sheath edge at nearly the system sound speed. They also predict that the small difference in drift velocity between the two species is insensitive to relative ion concentrations for n_{Ar}/n_e between 0.2 and 0.7. When one ion species dominates, each ion species is predicted to reach the sheath edge at its own Bohm velocity. We report the first experimental test of this model.

Baalrud *et al.* calculated the enhancement of the collisional friction associated with the ion-ion instability, and incorporated that into the ion momentum equation. They found that the collisional friction would bring the two species' drift velocities closer together until the velocity difference reached a critical velocity given by

$$\Delta V_c = |V_2 - V_1| = \sqrt{\frac{1+\alpha}{2\alpha}}\sqrt{v_{T1}^2 + \alpha v_{T2}^2}, \qquad (1)$$

where $\alpha = n_1 M_2/(n_2 M_1)$. Note that in the limit that $T_i/T_e \rightarrow 0$ both species are lost at the system sound velocity. The theory makes several approximations, the most important of which was using the fluid approximation for ΔV_c.

A schematic diagram of the experiment is shown in Fig. 1. The experiments were carried out in a multidipole chamber surrounded by 12 rows of permanent magnets on its cylindrical surface. Gas atoms were ionized by energetic electrons emitted from a set of hot thoriated tungsten filaments biased at -60 V with respect to the grounded chamber wall. A stainless steel plate of radius 7.5 cm was located along the axis of the chamber biased at -50 V. A 0.75 radius hole backed by a razor blade stack beam dump was located in the center of the plate. The plate was displaced in a direction parallel to the incident laser beam to measure the ion velocity as a function of position, while the collection optics and the photomultipler tube remained fixed [12]. In addition, a 8 cm $\times$ 12 cm razor blade stack antireflector was placed on the axis of signal collection of the photomultipler tube to reduce stray light reflection off the chamber wall. The LIF measurement system is described in more detail in previous papers [12,15].

Two tunable diode lasers were used. For argon ion velocities, a laser with (vacuum) wavelength centered on 668.614 nm was employed to stimulate the transition from the Ar+ metastable state, $(^3P)3d^4F_{7/2}$, to the excited state, $(^3P)4d^4D^o_{5/2}$. The observed decay to the $(^3P)4s^4P_{3/2}$ produced a 442.72 nm photon (air wavelength). For xenon ion velocities, a laser centered on the (air) wavelength 680.574 nm was used to excite the Xe+ metastable state, $5p^4(^3P_1)5d[3]_{7/2}$, to the $5p^4(^3P_1)6p[2]^o_{5/2}$ state. The transition to the $5p^4(^3P_1)6s[1]_{3/2}$ state produced the detected photon at 492.15 nm (air wavelength). The only change of setup in this experiment was that in addition to a iodine cell, an etalon was used to help calibrate detuning, $\Delta f = f - f_0$, where f_0 is the frequency of stimulated absorption for an ion at rest in the lab frame.

An emissive probe was used to measure the plasma potential with the inflection point method [16] in the limit of zero emission. The sheath-presheath boundary was identified at the position where the slope of the inflection points changed [17] from increasing to decreasing with emission. A Langmuir probe was used to determine the electron temperature which exhibited a bi-Maxwellian distribution as was found in previous experiments. Ion concentration ratios were determined by continuous wave (cw) ion acoustic wave (IAW) diagnosis described elsewhere [18].

Depending on experimental conditions, 5 to 50 LIF traces were taken, averaged and converted into an ion velocity distribution function (IVDF) using the first order Doppler shift, $v = \lambda\Delta f$. First moments were taken from the IVDFs to determine drift velocities ($v_d = \langle v\rangle$) for comparison with theory. Here we present the fluid moment corresponding to the drift velocity rather than the rms velocity given in our previous papers [12,19] to make comparisons with the theory.

Figure 2 shows the measured drift velocities at the sheath edge of the xenon and argon ions, with respect to the ion concentration ratio. The total pressure for this data set was 0.7 mTorr. As shown, within experimental uncertainty, the velocities differ slightly for approximately equal ion concentrations. This result is consistent with previous results [12]. However, when either ion concentration greatly differs from the other, each species leaves the plasma at its own Bohm velocity. This is a new experimental result.

The system velocity is also shown as a function of argon ion concentration ratio. As expected, the system sound velocity was determined by the majority species when one species dominates the plasma. The composition of the argon and xenon neutral gas with respect to their ion concentration are shown in Fig. 3. The electron temperature for all concentrations was found to be 0.70 ± 0.03 eV. Note the much higher xenon ion ratio at neutral ratios lower than 60%. Penning ionization of xenon by argon produced a higher xenon ion concentration ratio than the neutral concentration ratio. The ion temperature was found to vary with α as shown in Fig. 4. The ion temperature was

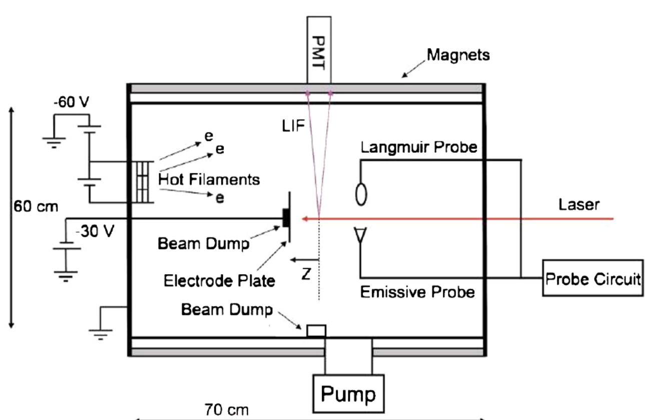

FIG. 1 (color online). Schematic diagram of the experimental setup.

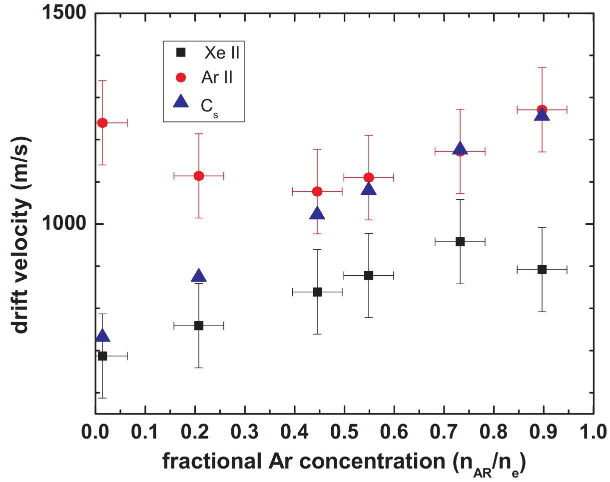

FIG. 2 (color online). Measured drift velocities and system sound velocities with respect to the argon ion concentration ratio.

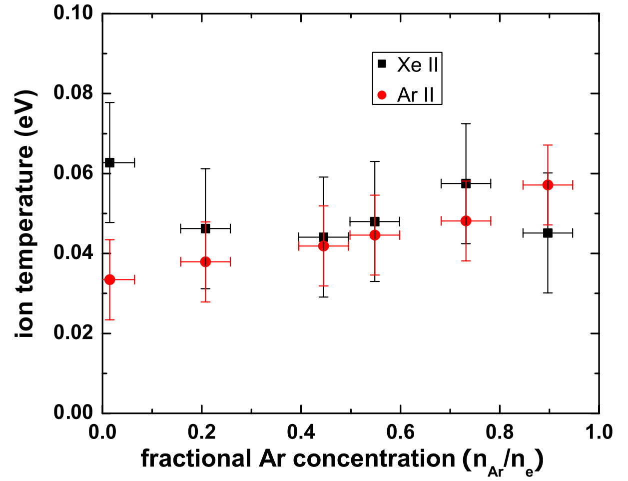

FIG. 4 (color online). Ion temperature graphed versus argon ion concentration.

estimated from the first and second moments of the IVDFs, $T_i = m_i(\langle v^2\rangle - \langle v\rangle^2)/2$. The ion temperature of each species fell, on the whole, with its own neutral pressure, consistent with the dominance of resonant charge exchange collisions.

A comparison of the experimental measured drift velocities for argon and xenon ions versus relative argon ion concentration with theory curves based on the predictions of Baalrud *et al.* are given in Fig. 5. Theory curves correspond to ion temperatures of 0.005 eV (solid), 0.01 eV (dashed) and 0.015 eV (dotted). It is apparent that the best fit lies between 0.01 eV and 0.005 eV. Note that there is very good qualitative agreement with the variations with the argon concentration but the best ion temperatures lie well below our measured temperature of approximately 0.05 eV. Also note the system sound velocity is in good agreement with the argon drift velocity for n_{Ar}/n_e greater than or equal to 0.5, consistent with our previous measurements, and that the separation of velocities is insensitive to the argon concentration for ratios ranging from 0.3–0.8.

The good agreement of the Baalrud *et al.* theory with the experimental data assuming the ion temperature is very low suggests that either the theory is basically correct but the details of the ion temperature dependence need improvement or that there is a systematic error in the experimental data. It is certainly unlikely that the ion temperature is lower than room temperature (0.025 eV). Further, the theory makes several simplifying approximations. Baalrud *et al.* very recently refined the theory to include a kinetic dispersion relationship for the instability (assuming that the IVDFs are Maxwellian) into the prediction of ion drift

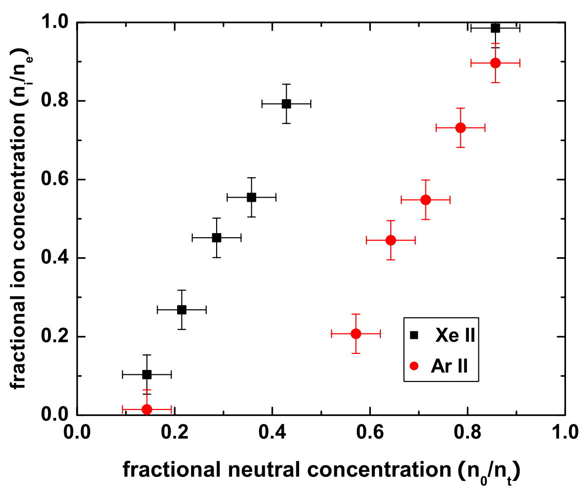

FIG. 3 (color online). Ion concentration ratios, determined by IAW diagnosis, graphed versus ratio of species neutral concentration to total neutral concentration.

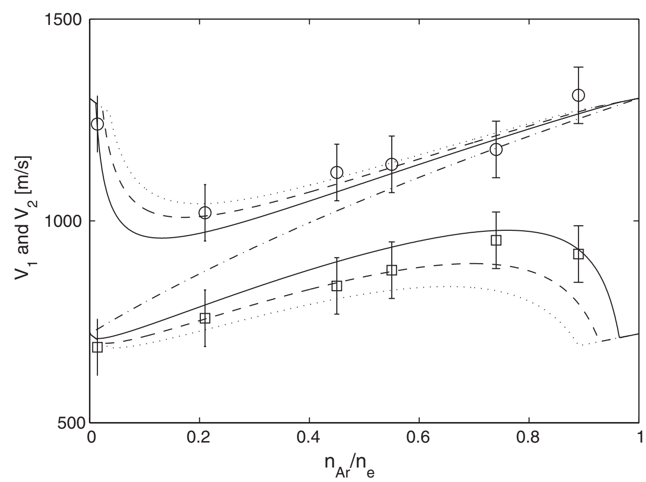

FIG. 5. Circles and squares are the measured argon and xenon velocities, respectively. Lines are prediction curves with ion temperatures of 0.005 eV (solid), 0.01 eV (dashed) and 0.015 eV (dotted). The solid line in the middle is the system sound velocity.

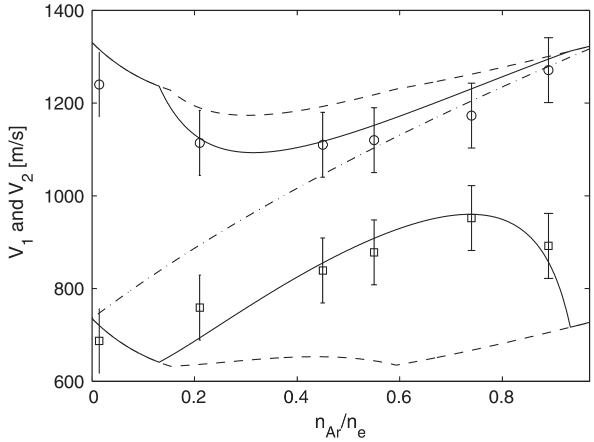

FIG. 6. Comparison of data and the prediction of the revised theory. The circles are the measured argon drift velocity and the squares are the measured xenon drift velocity. The solid line is the new prediction while the dashed line is the old prediction. The system Bohm velocity is represented by the dashed dotted line.

velocities [20], which results in the magnitude of the ion drift velocity differences being given by

$$\Delta V_c = -\frac{3}{2}|v_{T2} - v_{T1}| + \sqrt{\frac{1}{2}\left(v_{T1}^2 + v_{T2}^2 + \frac{n_2 T_1}{n_1 T_2} v_{T1}^2 + \frac{n_1 T_2}{n_2 T_1} v_{T2}^2\right)}. \quad (2)$$

In Fig. 6, this prediction was compared with our data fit with the observed xenon ion temperature of approximately 0.05 eV and argon ion temperature of approximately 0.043 eV, as shown in Fig. 6. It is apparent that the observed drift velocities and the prediction are in excellent agreement. This provides strong support for the argument that instability-enhanced collisional friction between ion species in the presheath of weakly collisional plasma with two ion species causes both ion species to be lost at close to the system sound velocity over a wide range of relative concentration. It also shows that when the concentration ratios are very large, each species is lost at close to its own individual Bohm's velocity, a feature not previously observed.

This work was supported by U.S. Department of Energy Grants No. DE-FG02-97ER54437 and No. DE FG02-03ER54728, National Science Foundation Grants No. CBET-0903832, and No. CBET-0903783.

*hershkowitz@engr.wisc.edu
†severn@sandiego.edu

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