Ion Diffusion Velocity Measurements in a Multi-Ion-Species Plasma Shock

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Collisonal plasma shocks generated from supersonic flows are an important feature in many astrophysical and laboratory high-energy-density plasmas. Compared to single-ion-species plasma shocks, plasma shock fronts with multiple ion species contain additional structure, including interspecies ion separation driven by gradients in species concentration, temperature, pressure, and electric potential. We present time-resolved density and temperature measurements of two ion species in collisional plasma shocks produced by head-on merging of supersonic plasma jets, allowing determination of the diffusion velocity of the ion species. Our results demonstrate that the lighter ion species diffuse faster than the heavier species within a shock front, consistent with predictions from the inter-ion-species transport theory. Results from the experiment approach quantitative agreement with theoretical prediction and 1D ion-Fokker-Planck kinetic simulation.

Introduction.—Shocks generated from supersonic flows are abundant in a variety of plasma environments, including astrophysical and laboratory high-energy-density (HED) laboratory experiments [3–6]. Compared to hydrodynamic shocks, plasma shocks may be governed primarily by Coulomb interactions between charged particles (collisional plasma shocks) [7] or by the influence of the electromagnetic fields (collisionless shocks) [8]. In addition, kinetic effects occurring in plasma shocks usually cannot be fully described using hydrodynamic shock theory and standard equation-of-state (EOS) models [9–12]. When multiple ion species are present in a collisional plasma shock, additional features can be introduced to the shock front structure, one of which is interspecies ion separation [13–16]. These effects have been studied in the context of inertial confinement fusion (ICF) experiments, in which mixtures of deuterium and tritium (DT) are compressed by strong shock waves to achieve fusion reactions. These shocks drive ion species separation through inter-ion-species diffusion [17], to the potential detriment of the fusion reactivity.

Work has been carried out to investigate multi-ion-species shocks and species separation in theory, simulation and experiment. A strong base of theoretical prediction is available on the diverse effects in multispecies plasma shocks: Kagan and Tang explored effects of electric field and temperature gradients on inter-ion-species transport [18, 19], Simakov et al. derived analytical solutions for weak planar shocks [11]. Furthermore, ion-kinetic simulations provide a powerful capability to explore the physics, although understanding effects of dimensionality and treatment are not routine. Keenan et al. employed an ion-kinetic code to study collisional planar shocks in two-ion plasmas [20]. Comparatively few experiments have been performed that have been able to study the structure inside a collisional multi-ion-species plasma shock [16, 21–24].

In this Letter, we report the first detailed experimen-
flux, driven by the respective gradients in total ion pressure $p_i$, ion temperature $T_i$, electron temperature $T_e$, and electrical potential $\Phi$. Expressions for the solution of the respective diffusion coefficients $D$, $\kappa_p$, $\kappa_T$, $\kappa_P$, and $\kappa_E$, have been pursued using kinetic theory with concessions to a Maxwellian, and are listed in Refs. [11, 19]. Values for some of the coefficients are obtained in practice by numerical solution [16].

At the shock boundary, Eq. (2) predicts that all the diffusion flux terms for the lighter ion species point from the post-shock region to the pre-shock region except the relatively small electron thermo-diffusion flux, resulting in a net flux pointing in the same direction. Therefore, to satisfy the condition $\sum \alpha = 0$, the diffusion flux for the heavier ion species has to point in the opposite direction in the center-of-mass frame, causing the ion species to separate in the plasma shock [16].

**Experiment.**—To experimentally investigate species separation within a shock front, we create multi-ion-species plasma shocks by colliding two plasma jets head-on in a cylindrical vacuum chamber of 137 cm length and 76 cm diameter. The jets are produced by capacitor-driven plasma guns which accelerate plasma via $j \times B$ force [25, 26]. At the time when the plasma guns are fired, a gas puff consisting of 50% Ar and 50% N$_2$ by volume (58.8% Ar and 41.2% N$_2$ by mass concentration) is first pre-ionized in the gun nozzle and then accelerated into the vacuum chamber, to a speed of $v_{ion} = 18$ km/s. Each individual jet collides with an ion density $n_i \approx 5 \times 10^{14}$ cm$^{-3}$, electron and ion temperature $T_i \approx T_e \approx 2$ eV, and mean charge $Z \approx 1$ [16]. The Mach number is thus $\sim 8.2$ for Ar and $\sim 4.9$ for N in the pre-shock region.

The top view of the experimental setup is depicted in Fig. 1(a). A five-chord heterodyne interferometer is used to measure the time-resolved line-integrated electron density in the plasma shock [27, 28]. The laser emission is produced using a 320 mW, 561 nm solid state laser, which is divided into multiple lower-power beams and injected into the chamber through five single-mode fiber optic cables. Each probe beam is $\sim 0.3$ cm in diameter and placed horizontally in the midplane of the chamber at 0, 2, 4, 6, 8 cm with respect to the center. The first four probe beams are directed into the chamber perpendicularly to the side window (parallel with the shock front) while the fifth at an angle of $75^\circ$. These chord angles are chosen so that we can use chord 5 to measure the average electron density in the plasma shock and chords 1 – 4 to determine the bulk flow velocity in the post-shock region via time-of-flight analysis, as well as allow insight into the radial expansion of the post-shock plasma. After passing through the plasma, the probe beams are compared with a reference beam of the interferometer in the Mach-Zender configuration, and the line-integrated electron density is computed based on the relative phase shift [29].

As the density in our plasma shock is not high enough for Stark broadening to be appreciable, Doppler broadening caused by ion thermal motion becomes the dominant source of spectral line broadening in the plasma [30]. A high-resolution spectrometer is utilized to measure the ion temperature in the shock through examining the width of the Doppler-broadened ion lines. The light emission from the plasma is collected using two collimators of $L = 2$ cm in diameter. Chord 1 is aligned with the central vertical plane of the chamber and held at 5 cm above the horizontal midplane, whereas chord 2 is in the vertical midplane but at an angle of $\sim 45^\circ$ with respect to the horizontal plane, as shown in Fig. 1. The light collected is then fielded by a double-pass high-resolution monochromator (McPherson 2062DP) with 2400 mm$^{-1}$ grating, and the resulting spectrum is captured using a charge-coupled-device (CCD) camera (PCO Pixelfly). The ion temperature in our plasma shock is estimated based on the measured Doppler broadening of ArII 434.9 nm and NII 399.6 nm lines of Chord 2, which removes contributions to the broadening from the post-shock plasma radial expansion. In the experiment, we find that the width of the ion Doppler profile obtained from chord 1 is about 1.5 times as that obtained from chord 2 due to the plasma expansion in the radial direction, as shown in

![Diagram](attachment://fig1.png)
The ion emission spectrum is also used to infer the time-resolved density of each ion species in the plasma shock. For an atomic transition from an excited energy state to the lower state, the intensity of the emitted photons is proportional to the density of the excited state, a function strongly dependent on plasma parameters, such as the electron density and temperature [31]. In our case where the electron temperature stays about the same in the pre- and post-shock region, the density of the excited state can be assumed proportional to the total ion density to the zeroth-order approximation. The relative density of each ion species, therefore, can be inferred by monitoring the intensity of the Doppler-broadened spectral lines of each species.

Other diagnostics used in the experiment include a photodiode array at each gun nozzle to measure the jet velocity, a visible diagnostic spectrometer to interpret the electron temperature, and a fast intensified-CCD camera (PCO DiCam Pro) to image the shock formation. The diagnostic spectrometer records the broadband ion emission spectrum, which is then compared to PrismSPECT non-local-thermodynamic-equilibrium (non-LTE) model-spectra, which are used in time-of-flight analysis to determine the plasma bulk flow velocity in post-shock region. (c) Example of Doppler-broadened ArII 434.9 nm line. The orange curve shows the instrumental broadening of the same line without the Doppler effects. (d) Comparison between Doppler-broadened ArII 434.9 nm lines obtained from chord 1 and 2 of Doppler spectroscopy. The center of profiles in (c) and (d) is shifted to 0 nm.}

FIG. 3. (a) Example of broadband ion emission spectrum from the diagnostic spectrometer, along with the calculated spectrum using PrismSPECT at $T_\text{e} \approx 2.2$ eV. (b) Example of line-integrated electron density from interferometry. The peak line densities of chord 1, 2, and 3 are marked by stars, which are used in time-of-flight analysis to determine the plasma bulk flow velocity in post-shock region. (c) Example of Doppler-broadened ArII 434.9 nm line. The orange curve shows the instrumental broadening of the same line without the Doppler effects. (d) Comparison between Doppler-broadened ArII 434.9 nm lines obtained from chord 1 and 2 of Doppler spectroscopy. The center of profiles in (c) and (d) is shifted to 0 nm.

One of the most important findings of this experiment is the observations of species separation within the plasma shock. Figure 4(a) shows the normalized density of Ar and N by the maximum values as a function of time, where the pre- and post-shock regions are separated by a blue dashed line. The density of both ion species increases at the same rate within errors at early time; however, at later time as the shock forms, the density of N ions decreases faster than that of Ar ions. This finding suggests that the lighter ion species (N) diffuse faster in the plasma shock gradients, consistent with the theoretical predictions. To bound the ion diffusion velocity, we consider the ion flow caused by plasma expansion and diffusion at the boundary of the collimator viewing volume shown in Fig. 1(b). In the radial direction, the ions enter and leave the volume, resulting in no net change of the ion density. Hence, the ion diffusion in the axial direction becomes the only major mechanism that decreases the ion density in the viewing volume. If we assume that the diffusion velocity remains relatively constant shortly after the shock forms, then according to the continuity equation, the decrease of the normalized ion density should follow the exponential law $e^{-2u_\text{t}/L}$, where the length scale $L$ is the diameter of the collimator.

By fitting the ion density in Fig. 4(a) from 58 to 65 µs, we find that the diffusion velocity for Ar and N is $u_{\text{Ar}} = (0.8 \pm 0.1) \times 10^3$ m/s and $u_{\text{N}} = (1.1 \pm 0.2) \times 10^3$ m/s, respectively. We
also estimate the plasma bulk flow velocity in the post-shock region \( u = \sum \alpha_i c_\alpha u_\alpha \approx 920 \text{ m/s} \), in agreement with the velocity of \( \sim 1100 \text{ m/s} \) determined using time-of-flight analysis from the interferometry chords shown in Fig. 3(b). Thus, the diffusion velocity for Ar and N in the center-of-mass frame is \( v_{\text{Ar}} = u_{\text{Ar}} - u \approx -120 \text{ m/s} \) and \( v_{\text{N}} = u_{\text{N}} - u \approx 180 \text{ m/s} \), with the relative diffusion velocity \( \Delta v = v_{\text{N}} - v_{\text{Ar}} \approx 300 \text{ m/s} \).

We evaluate the diffusion flux terms in Eq. (2) based on the experimental results to further understand their effects on species separation. The gradient of quantity \( Q \) is computed as \( \nabla Q/Q \approx 2(Q_2 - Q_1)/L(Q_2 + Q_1) \), where the subscript 1 and 2 represent the pre- and post-shock region, respectively. We also assume that the initial concentration separation \( \nabla c \approx 0 \) for simplicity. The diffusion coefficients, calculated either analytically or numerically [16, 18, 19], are \( D \approx 4.12 \text{ m}^2/\text{s} \), \( \kappa_T \approx 0.28 \), \( \kappa_E \approx 0.28 \), \( \kappa_{\text{T}} \approx -0.06 \), and \( \kappa_E \approx 0.28 \). Since the ambipolar electric field in Eq. (2) can be estimated as \( \nabla \Phi = \nabla T_e/e [34] \), the contributions of each flux term to the diffusion velocity of N ions in the center-of-mass frame are \( 233 \text{ m/s} \) for baro-diffusion, \( 199 \text{ m/s} \) for ion thermo-diffusion, \( -3 \text{ m/s} \) for electron thermo-diffusion, and \( 4 \text{ m/s} \) for electro-diffusion, with a total diffusion velocity \( v_\text{N} \approx 400 \text{ m/s} \). Similarly, the diffusion velocity for Ar in the center-of-mass frame is \( v_{\text{Ar}} \approx -300 \text{ m/s} \), resulting in a difference of \( \sim 700 \text{ m/s} \), relatively consistent with our experimental value. The above calculations suggest that both baro- and ion thermo-diffusions dominate over other diffusion terms, comparable to the mechanisms that drive species separation in ICF experiments [19].

We also experimentally measure heating of the distinct ion species. Figure 4(b) shows the time evolution of Ar and N ion temperature inferred from Doppler spectroscopy. Substantial ion heating and temperature separation are observed during the shock formation, with the temperature elevated from 2 eV to \( \sim 17 \text{ eV} \) for Ar and to \( \sim 9 \text{ eV} \) for N. Since the ion thermal energy is mainly transferred from its own kinetic energy, a ratio of \( \sim 2 \) in thermal energy gain is found between Ar and N as a result of their mass ratio \( \sim 2.9 \), indicating that some energy loss and equilibration occurring in the earliest collisions and formation time of the shock. Subsequent decrease of the ion temperature is observed due to classical thermal equilibration [30] among both ion species and electrons, with electrons radiatively cooling the plasma in the optically thin conditions.

A 1D Eulerian Vlasov-Fokker-Planck simulation is performed using the iFP code [20, 35, 36], as shown in Figs. 4(c)–4(d), to compare with the experimental results. The simulation in general agrees with the experimental data, successfully predicting a faster density decrease of N, ion heating, and temperature separation in the post-shock region shown in Figs. 4(a)–4(b). One of the noticeable discrepancies between the simulation and experiment is that the simulation predicts a higher ion temperature jump than the data. In the simulation, leading edge ions with a faster velocity reach the center of the chamber first and are heated to a high temperature, as shown in Fig. 4(d) at \( \sim 50 \mu\text{s} \). This effect can be easily seen in the simulation, but difficult to be observed in the experiment because of the low density of this ion group (Fig. 4(c) at \( \sim 50 \mu\text{s} \)). In addition, the 1D simulation does not admit the possibility of radial expansion of the post-shock plasma, which is clearly seen in the experiment. This effect provides another mechanism by which kinetic energy is lost from the post-shock region, and contributes to the lower temperatures observed experimentally. It should be noted that the ion temperature separation demonstrated in Figs. 4(b) and 4(d) is a higher-order effect in deviations from LTE, whereas the diffusion flux theory assumes that all ion temperatures are equal [11]. Analyzing the simulation output, the average diffusion velocity for N and Ar in the center-of-mass frame is \( v_N = 300 \text{ m/s} \) and \( v_{\text{Ar}} = -260 \text{ m/s} \), respectively. The total relative velocity is thus \( \Delta v = 560 \text{ m/s} \).

![Figure 4](image_url)

**FIG. 4.** (a) Measured ion density from chord 1 of the Doppler spectrometer as a function of time. The density is normalized by the peak value in each curve, marked by the blue vertical dashed line that separates the pre- and post-shock regions. (b) Measured ion temperature from chord 2 of the Doppler spectrometer as a function of time, demonstrating ion heating and temperature separation. The green horizontal dashed line represents ion temperature in the pre-shock region. (c) Simulated ion density as a function of time using the iFP code. The density is normalized by the peak value in each curve. (d) Simulated ion temperature as a function of time. The color bands in (a) and (b) indicate one-standard-deviation uncertainties.

| Diffusion Velocity [m/s] | Experiment | Theory | Simulation |
|--------------------------|------------|--------|------------|
| \( \Delta v \)           | 300 ± 200  | 700    | 560        |
in agreement with both of the experimental results and theoretical predictions. The comparison of the relative diffusion velocity for Ar and N in the experiment, theory, and simulation approaches described can be found in Table I.

Conclusions.—We present the first experimental study of the density and temperature evolution of Ar and N in collisional multi-ion-species plasma shocks. With measurements that resolve the diffusion velocity of each ion species, we demonstrate that the lighter species, in our case N, diffuse faster in a shock front, in agreement with theoretical understanding. The relative diffusion velocity is able to be calculated and found comparable with our experimental results. Furthermore, we find that significant ion heating occurs on the separate ion species during the formation of the shocks, with a temperature jump of \( \sim 15 \text{ eV} \) for Ar and \( \sim 7 \text{ eV} \) for N, similar to the initial distribution of jet kinetic energy but not simply proportional. We compare our experimental results with 1D Vlasov-Fokker-Planck simulation, and find that in general the calculation reproduces the experimental data, with differences that can be understood from the 3D geometry of the experimental plasma jets and shocks. This investigation on species separation in collisional plasma shocks provides useful new data to further understanding of multi-species plasma shocks and their relevance to HED/ICF configurations.

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