Charge-exchange X-Ray Signature in Laboratory Outflow Interaction with Neutrals

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Abstract

According to the principle of Euler similarity between laboratory and astrophysical plasmas, laboratory plasmas driven by high-power lasers have been used to simulate some aspects of astrophysical phenomena. In doing so, they aid our understanding of shock heating, interaction structures, and the consequential evolution for astrophysical outflows within a short timescale (∼ns). In this work, we experimentally investigated the mechanism of X-ray emission originating from a hot outflow (plasma) with a velocity of around 330 km s⁻¹, impinging on a cold medium. A hybrid model was set up to understand the high-resolution X-ray spectra taken at the interaction region and to deduce that charge exchange takes place in such a laboratory miniature of astrophysical outflow interacting with dense molecular clouds, as in the cases of HH 248 and Cap in M82, for example. Effects from targets with multiple electrons are also explored. A brief analysis has been performed for our laboratory analog and astrophysical objects by a dimensionless ratio of the length scale between X-ray-emitting and charge-exchange regions.

Unified Astronomy Thesaurus concepts: Laboratory astrophysics (2004)

1. Introduction

Ryutov et al. (1999, 2000) demonstrated that two different systems described by equations of ideal magnetohydrodynamics evolve similarly when they satisfy a number of dissipation criteria (e.g., negligible heat conduction, viscosity, and radiation). Since then, many laboratory experiments have been performed using high-power lasers or Z-pinch facilities to model some astrophysical phenomena, e.g., jet formation in Herbig-Haro (HH) objects (Albertazzi et al. 2014; Yuan et al. 2018), jet evolution in the Crab Nebula (Li et al. 2016), accretion dynamics in young stars (Cross et al. 2016; Revet et al. 2017), collisionless shocks in supernova remnants (SNRs; Nicolaël et al. 2009; Yuan et al. 2017), and so on.

Outflow/jet interaction with surrounding media is a common physical process in many astrophysical objects (Pravdo et al. 2001, 2004, 2009) and was suggested to be responsible for the source of X-rays from HH objects (Bonito et al. 2004). Obvious X-ray brightening at the border of SNRs was recognized to be due to the hot ejected plasma interacting with interstellar media (Katsuda et al. 2012). Nicolaël et al. (2008) and Nicolaël et al. (2009) reported laboratory studies for the outflow interaction with gases (helium and argon) and revealed that the surrounding gas can have a collimating effect on the outflow/jet propagation and the formation of bow shocks (Gregory et al. 2008). In young stellar objects (YSOs; e.g., classical T Tauri stars), X-ray emission was suggested to be caused by the accretion infall impinging on the stellar surface (Telloni et al. 2007). Revet et al. (2017) performed an experiment using a high-power laser facility to explain the anomalous X-ray emissions in YSOs, where supersonic plasma flow was guided by strong magnetic fields (B = 20 T) to impact on a solid object. In that work, obvious X-ray emission was detected from the interaction region and was mainly attributed to being from the infalling plasma, where X-ray emission was proposed to be due to recombination as the plasma cooled.

Liang et al. (2018) performed a similar experiment using the Shengguang-II facility to explore the X-ray origin from HH 248 with the aid of scaling laws (Ryutov et al. 1999), where a number of critical parameters are comparative for the two different cases. By adjusting the material of the target and by using high-resolution spectroscopy, the X-ray emission from the interaction zone was confirmed to originate from outflow. However, the full mechanism of the X-ray emission was not clear.

In this work, a sophisticated atomic model was developed to explain our laboratory measurements. In Section 2, the experimental measurement is briefly described. In Section 3, the theoretical model for simulating the X-ray emission is outlined in detail. Some results and discussions are presented in Section 4. Finally, a summary and conclusion are given.
The experiment was performed at the Shenguang-II (SG-II) laser facility in Shanghai, China. Four laser beams with a total energy of \( \sim 1000 \text{ J} \), wavelength of \( \lambda = 0.351 \text{ \mu m} \), and duration of 1 ns were divided equally into two bunches. The experimental setup is illustrated as in Figure 1. The two bunched beams synchronously irradiated two sides of a K-shaped Al target (opening angle of 120°) with a separation of 400 \( \mu \text{m} \). Each bunch was focused to a spot size of 150 \( \mu \text{m} \), which yielded an intensity of \( 5.3 \times 10^{15} \text{ W cm}^{-2} \). The plasma outflow/jet was generated by two convergent supersonic expanding and flowing plasmas, which were produced by the lasers irradiating the aluminum K-shaped target, shown in Figure 1. The outflow velocity was about \( 330 \text{ km s}^{-1} \), being close to many stellar winds of hundreds or thousands of kilometers per second. In the direction of outflow/jet propagation, an obstacle target of 100 \( \mu \text{m} \) CH film was placed 1.6–4 mm away, and this was affixed onto an aluminum holder. The experiment was run both with and without the CH film. In the latter case, the outflow impinged on the Al holder, which remained in place at a distance of 3 mm from the K-shape target. For the CH film, strong X-rays from the two hot spots photoionized the CH surface and formed a low-temperature medium before the arrival of the aluminum outflow. Three kinds of diagnostic instruments monitored the interaction region from directions perpendicular to the outflow; they included two X-ray pinhole cameras with a beryllium window of thickness 50 \( \mu \text{m} \), a crystal spectrometer, and an optical diagnostic instrument. Such measurements have been done for different experimental shots over a 2 yr period with different collisional distances, confirming the repeatability and essential physics in such hot outflow interactions with a cold medium.

In Figure 2, the X-ray images from the two pinhole cameras using different lines of sight are presented to show the morphology of the hot outflow interaction with a low-temperature medium. According to the collisional model (Hartigan 1989), the working surface consisted of two principal shocks: a Mach disk that slowed the outflow, and a forward bow shock that accelerated the ambient medium, was separated into two regions by contact discontinuity, namely, shocked outflow and shocked ambient medium. By using different obstacles, Liang et al. (2018) revealed that the X-rays around the CH obstacle are from the shocked outflow. In studying SNRs, the brightness profile of X-rays was used to identify the position of contact discontinuity (Miceli et al. 2009). In our X-ray morphology, we adopted the same procedure and identified a clear bow-shape contact discontinuity and Mach disk (some references name the Mach disk to be reverse shock); see curves in Figure 2. We also noticed the symmetry break of the shocked outflow relative to the central line of outflow in the right panel of Figure 2, because this camera is tilted to the top side by 22.5° and the K-shape target. Both of them cause the outflow to be noncylindrical. Such an interaction morphology has been observed by single-energy Al He\( \alpha \) emissions covered by the crystal spectrometer; see the bottom panel of Figure 2.

By using a crystal spectrometer, we observed He\( \alpha \) lines from highly charged aluminum ions around the interaction region at different distances between the K-shape target and the CH film, as shown in Figure 3. Here, a rectangular extraction region, covering most emitted photons along the dispersion direction, is adopted to obtain spectra from the interaction region. Liang et al. (2018) noticed that the line intensity ratio \( \Omega \) between the \( i + j \) and \( r \) emission (here \( r \) is 1s2p\(^2\)P\(_{1}\) \( \rightarrow \) 1s\(^2\)S\(_{0}\) (1.598 keV) transition, \( i \) and \( j \) are 1s2p\(^2\)P\(_{1}\) \( \rightarrow \) 1s\(^2\)S\(_{0}\) (1.588 keV) transitions, and \( f \) is 1s2s\(^2\)S\(_{1}\) \( \rightarrow \) 1s\(^2\)S\(_{0}\) (1.575 keV) transition) of Al XII is higher than that at the laser hot spot and becomes more obvious at larger distances, as shown in the right panel of Figure 3 with more experimental data available. However, this observed line intensity ratio of 0.92 \( \pm \) 0.05 cannot be explained by a thermal model in this shocked outflow region; see the solid curve in the right panel of Figure 3. Hence, we suspect that the
process of charge exchange may be the possible reason. This experimental interaction is very similar to many stellar/galaxy outflows interacting with interstellar medium in SNRs (Katsuda et al. 2012), or starburst galaxies (e.g., M82; Tsuru et al. 2007; Liu et al. 2011; Zhang et al. 2014), or planetary atmospheres in the solar system (Lisse et al. 1996; Bhardwaj et al. 2007), where charge exchange has been regarded as the reason for the anomalous line intensity ratio $f/r \sim 4.0$ of He-like ions. Furthermore, in some galaxy clusters (e.g., Perseus), the unidentified line feature at 3.5 keV was suggested to be from charge exchange (CX) processes between hot cosmic plasma and cold neutral gas by Gu et al. (2015).

3. Hybrid Atomic Model for X-Rays

We set up a hybrid atomic model with the inclusion of charge exchange and electron impact excitation. The atomic model used to describe line emission from the aluminum target ($X^{q+}$, here $q = 11$) includes an upper-level population due to electron impact (de-)excitation, charge-exchange capture of $X^{(q+1)+}$ with neutrals or with lower charged ions, and subsequent radiative decays, either directly to the ground and lower excited states or via cascades, which is formulated as

$$\frac{d}{dt} n_{i}^{q+} = n_{i}\sum_{j>i} n_{j}^{q+}Q_{ji}(T_{e}) + \sum_{j>i} n_{j}^{q+}A_{ji}$$

$$-n_{i}^{q+}\left[ n_{j}\sum_{i<j} Q_{ij}(T_{e}) + \sum_{j<i} A_{ij} \right]$$

$$+n_{neu} n_{0}^{(q+1)+}C_{0j}(T_{e}),$$

where $n_{i}^{q+}$ is the number density of $q+$ charged ions at the $i$th level state, while $n_{e}$ and $n_{neu}$ correspond to the number density of electrons and neutral atoms/molecules, respectively. $Q_{ij}$ and $A_{ij}$ refer to the electron impact (de-)excitation rate coefficient and radiative decay rate for $i \rightarrow j$, respectively. $C_{0j} \equiv (v\sigma_{cx}(v))$ are the charge-exchange single-electron capture rate coefficients from $q$ + 1 charged ions in their ground state. $v$ is the relative collision velocity between $X^{(q+1)+}$ ions and neutrals, while $\sigma_{cx}(v)$ is the cross section for the charge-exchange process. The above complex coupled equation can be simplified to be

$$\frac{d}{dt} \tilde{N} = A \tilde{N},$$

Figure 2. The X-ray morphology of the outflow and its interaction with a low-temperature medium from the photoionized CH target recorded using wide-field pinhole cameras with an energy band above 1 keV, and by an X-ray spectrometer with spatial resolution in the outflow direction. Left: due western (W) pinhole camera. Right: southeastern (SE) pinhole camera tilted to top. Bottom: due eastern (E) spectrometer tilted to top. The y-axis is also the energy dispersion direction; see the right label with photon energy in keV. Note: the data are taken from different experimental shots over 2 yr with interaction distances of 3.3–3.6 mm.
where $A$ is a matrix composed of parameters of the various atomic processes mentioned above, and the $N$ vector is composed of the $n_i^{q+}$ (here the dimension is 287), the number density of $q$-charged aluminum ions. An assumption of equilibrium ($\frac{dN}{dt} = 0$) is adopted to obtain the level population and further the line emissivity $\epsilon_{ij} = n_i A_{ij}$. Since only triplet lines from He-like Al II are covered by our crystal spectrometer and discussed in this paper, electron capture from neutrals and collisional quenching are included for line emissivities of He-like ions. Collisional ionization and recombination are included separately for the charge distribution following the description in Liang et al. (2014).

For electron impact excitation, we used the data of Whiteford et al. (2001), which were implemented in the SASAL database as described by Liang et al. (2014), where the excitation data are up to 1s$^1$ and lower-lying levels. The level energies and radiative decay rates from the 1s$^1$ (n = 6–12) configurations are calculated by using FAC (Gu 2008).

For the charge-exchange data, Cumbee et al. (2014, 2018) developed a comprehensive charge-exchange database (namely, Kronos\textsuperscript{12}) by using realistic calculations of highly charged ion collisions with H, He, and H\textsubscript{2}, including the multichannel Landau–Zener, atomic-orbital close-coupling, molecular-orbital close-coupling, and classical trajectory Monte Carlo methods, where detailed comparisons have been performed with available measurements of charge transfer cross section. CX cross sections with multielectron targets (including H\textsubscript{2}O, CO, CO\textsubscript{2}, OH, and O) are also provided in the Kronos database by using the multichannel Landau–Zener method (Mullen et al. 2016, 2017). We adopt the CX cross sections from the Kronos database. Since the level energies and transition decays are stored in fine structures in SASAL for high-resolution spectral modeling as in other codes, e.g., APEC (Smith et al. 2001) and SPEX (Kaastra et al. 1996). So $n$-, $n\ell$, and $n\ell$S-resolved CX cross sections in Kronos are automatically matched and redistributed to the captured ions with fine-structure states according to different weights by a data import script. For He-like ions, the $n\ell$S-resolved cross sections are available, and then the statistical weight of the total angular momentum is used here. By using various available CX cross sections with inclusion of experimental measurements, Gu et al. (2016) obtained scaling laws for the charge ($q - 1$), collision energy ($v - 1$), and main quantum number $n$-dependent cross section, which significantly benefit the spectral modeling tool when realistic calculations of CX are not available:

$$\sigma_{cx} = a_0 q E_s a_1 \ln \left( \frac{a_5}{E_s} \right) \left( 1 + \frac{E_s}{a_5} \right)^{a_6},$$

where $E_s = E/q^{0.43}$ is scaled for the collision energy $E$ in eV amu$^{-1}$, and $a_0$ to $a_6$ are $q$-dependent fitting parameters. The $n$ dependence is described by a phenomenological third-degree polynomial formula as a function of $n_{nom}(n, q) = (n - n_q)/n_q$ where $n_q$ is the principle quantum number of the dominant capture channels in collisions with neutrals (Janey et al. 1983), and can be written by

$$n_q = \sqrt{\frac{I_H}{I_t}} \left( 1 + \frac{q - 1}{\sqrt{2q}} \right)^{-0.5},$$

where $I_H$ and $I_t$ are the ionization potentials of H and the target atoms, respectively.

For Al$^{2+}$ collision with neutrals, the dominant capture channels are $n = 6/7/8$ at the experimental outflow velocity of 330 km s$^{-1}$, as shown in Figure 4. Although the ionization potentials of H, OH, and CO$\textsubscript{2}$ targets are very close, the $n$-distributions of the cross sections with peak capture channel $n = 7$ differ from each other. The effects due to the collision targets have also been verified by experiments (Hasan et al. 2001; Xu et al. 2021). The results from the fitting parameters of Gu et al. (2016) give a peak capture channel of $n = 6$. There are obvious differences for the velocity-dependent total charge-exchange cross sections. The results from the fitting parameters

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\textsuperscript{12} www.physast.uga.edu/ugacxdb/
of Gu et al. (2016) are lower than the data taken from the Kronos database except for the data in the collision with the He atom.

4. Results and Discussions

4.1. Collisional Quenching and Charge Exchange

The left panel of Figure 5 shows the scheme of the level population of the He-like triplets. Besides the excitation from the ground state 1s2s 1S0, cascade populations from higher excited levels (n = 3–12) are considered, where the level population (n > 5) results from single-electron capture of H-like aluminum ions in collision with neutrals. Here we briefly discuss the spectral feature of the He-like ion due to its collision with thermal electrons and/or charge exchange with neutrals. For coronal plasmas, at a typical electron density of 1010 cm$^{-3}$ and electron temperature of 416 eV (Liang et al. 2018), the resonance r line intensity is the strongest of the He-like triplets; see the solid black curve in the right panel of Figure 5. The f line intensity is comparable to the resonance line intensity with a ratio f/r $\sim$ 0.9, which is consistent with stellar observations with values 0.8 $\pm$ 0.2 of Si XIII and other ions (Ness et al. 2002). With increasing electron density from 1010 to 1014 cm$^{-3}$, the forbidden f line is quenched, and it completely disappears at an electron density of 5.0 $\times$ 1019 cm$^{-3}$. For solar wind charge-exchange emissions with planetary exospheres, e.g., Martian’s X-ray observation (Dennerl et al. 2006; Koutroumpa et al. 2012) and theoretical charge exchange emission (CXE) modeling (Smith et al. 2012, 2014; Liang et al. 2014; Mullen et al. 2017), the forbidden f line intensity of He-like ions is significantly stronger than the resonance r line intensity; see the dark-blue line in Figure 5. This is completely different from the case of a coronal plasma and is regarded as an important tracer or probing method for the interface of hot outflow and cold medium in astrophysics (Lallement 2004; Katsuda et al. 2012).
In this experiment, the outflow plasma is thinner than that at the laser hot spot, but its density is still enough to quench the 1s2s$^2$S$_1$ population and relatively enhance the population of 1s2p$^3$P$_{1,2}$ levels; see the left panel of Figure 5. Another reason is the long lifetime (6.0 $\mu$s) of the 1s2s$^2$S$_1$ level, which is significantly larger than the lifetime (~10 ns) of our laboratory plasma. So we cannot observe the forbidden line $f$ in the interaction region of the experimental hot outflow with the cold medium. Here the electron temperature (416 eV) is estimated from a purely collisional model using the He$^3$/Ly$\alpha$ line ratio of Al ions. In a hybrid model such as this, the charge exchange will increase the recombination rates and enhance the He$^3$/Ly$\alpha$ line ratio at a given temperature. The observed ratio implies that the electron temperature at the interaction region will be lower than that (416 eV) used here. This ratio is also velocity dependent, as discussed in following subsection for the $(i+j)/r$ ratio in Figure 7.

In this hybrid atomic model, namely, excitation plus charge exchange, the intercombination transition $i$ and $j$ lines are enhanced efficiently; see the orange curve in Figure 5. For comparison, the experimental spectrum using the CH obstacle at a distance of 4.0 mm is also overlayed by symbols with error bars. Here, we derive the uncertainty (~20%) by using different region widths for spectral extraction because only one-shot measurement for a given collisional distance is realistic on such a large laser facility. This uncertainty results from the spatial resolution and nonuniformity along the jet direction as shown in the right panel Figure 2, as well as the extraction selection for spectra. By multiple measurements and steady laser conditions, the uncertainty could be smaller. The experimental line width adopted in this figure is 6.6 $\pm$ 0.5 eV.

By using optical interferometric data, Liang et al. (2018) obtain an outflow density of about $(2-3.5) \times 10^{19}$ cm$^{-3}$. At the interaction region, the electron density is higher than its ambient medium (Dizière et al. 2015). A combination of electron density of $4.2 \times 10^{19}$ cm$^{-3}$ and neutral density (H atom) of $5.0 \times 10^{17}$ cm$^{-3}$ can make the theoretical spectra consistent with this experimental one measured at a collisional distance of 4.0 mm. So the charge-exchange process may be the reason for the anomalous line intensity ratio at this experimental interaction zone.

### 4.2. Line Intensity Ratio $(i+j)/r$

By using the charge-exchange cross section from the Kronos database (see footnote 1) and other atomic data described in the above section, we calculate the line intensity ratio $(i+j)/r$ by using the hybrid model at electron and neutral hydrogen density grids with steps of 0.03/0.05 (in log) in the range of $10^{18}-10^{21}$ cm$^{-3}$ and $10^{15}-10^{18}$ cm$^{-3}$, respectively; see the top left panel in the contour plot of Figure 6. Liang et al. (2018) diagnosed the electron temperature to be 416 eV at the interaction zone, which is used to obtain the electron impact excitation rates in this calculation. The experimental outflow velocity of 330 km s$^{-1}$ is used to calculate the charge-exchange rates. In this contour plot, the line intensity ratios for collisions with other targets are presented, which will be discussed in the next subsection. The experimental ratios of 0.69 $\pm$ 0.07 and 0.92 $\pm$ 0.05 at distances of 3.2 and 4.0 mm, respectively, are overlaid by lines. It is obvious that the line intensity ratio is sensitive to the electron density, while being less sensitive to neutral density, and approaches saturation above neutral density of $10^{16}$ cm$^{-3}$.

In the measurements, we noticed an increasing trend of the $(i+j)/r$ ratio caused by increasing the interaction distance; see symbols with error bars in Figure 3. With an increase of the interaction distance, the outflow/jet needs a longer time to interact with the cold medium. During its propagation, the hot outflow also expands in the radial direction. This will result in the electron density decreasing at a longer interaction distance. This is also consistent with the present hybrid calculation that the $(i+j)/r$ ratio increases with decreasing electron density at a given neutral density.

Since the charge-exchange cross section is dependent on the collision velocity ($v_c$) and electron impact excitation is a function of electron temperature ($T_e$), we also explore the dependence of the ratio $(i+j)/r$ on the electron temperature and collision velocity at two groups of electron and neutral densities, e.g., low- and high-limit neutral densities in Figure 6 corresponding to an experimental ratio of 0.92 $\pm$ 0.05. In Figure 7, we present this ratio in collisions with H and He atoms. Velocity dependence and temperature dependence are completely different from each other at the two different density groups. For the high-density group, the ratio is less sensitive to the collision velocity below $T_e = 300$ eV, while it is sensitive to electron temperature over the illustrated $T_e$ range. This is consistent with the general understanding that electron quenching becomes more obvious at high electron density. For the low-density group, the ratio is sensitive to both electron temperature and collision velocity, that is, the contribution from charge exchange becomes comparable to electron excitation. For different targets, the temperature and velocity dependences differ from each other. In summary, the four physical parameters ($n_e, n_H, T_e$, and $v_c$) for electron excitation and charge exchange determine the observed line intensity ratio $(i+j)/r$. This makes its diagnostic application more complicated.

### 4.3. Effects from Multiple-electron Targets

In the experiment, strong X-rays from the hot laser spots will photoionize the cold medium, and a rapid recombination will occur owing to radiative cooling around the dense CH wall before the arrival of the outflow. Then, the electron donors in the heavy ion collisions are mainly from hydrogen and carbon atoms, as well as singly charged carbon ions ($C^+$ with ionization potential of 24.38 eV, being close to that of He atoms). The contribution from higher charged carbon ions can be expected to be negligible owing to the higher ionization potentials. For example, for $C^{2+}$, the ionization potential is 47.8 eV. According to the scaling laws of Janey & Gallagher (1984),

$$\sigma_{C^{2+}} = \frac{N_c^{2+}}{N_{He}} \left(\frac{V}{V_{24}}\right)^2 \sigma_{He},$$

the CX cross section in collisions with higher charged carbon ions is estimated to be less than 8% than that in the collision with H atoms, because there is no CX cross section available for collisions with carbon atoms. Oxygen atoms ($^1P$) have a similar open-shell structure to carbon atoms (1$^3S^2$, 2$^3P$), so the spectral analysis with CX data for oxygen can provide insight into the behavior of collisions with carbon atoms. The ionization potential of He atoms is comparable to that of $C^+$ and can be used for the Al$^{12+}$ collision with the $C^+$ ions. But this kind of collision (Al$^{12+}$-$C^+$) is completely different from collisions with neutral He atoms owing to the Coulomb repulsive force between two positive ions. This assumption may be a large uncertainty of 20% or more.
Mullen et al. (2017) listed relative line intensities by pure CXE modeling for the He-like triplets including AlXII ions with different targets. The targets play an important role for line intensity ratios \((i+j)/r\), which vary obviously for the different targets, and there is no relation to ionization potentials; see Figure 8. The collisions with H atoms will result in a high line intensity ratio of \(6.6–6.8\), while the intensity ratio is about \(1.5–2.0\) in the collisions with H2O, CO, CO2, and H2. The effects resulting from the collisional velocity seem weak. All the pure CXE predictions with different targets are higher than the experimental values of \(0.65–0.92\), and the forbidden f line is strongest, while it disappears completely in this experiment. Electron impact excitation has to be considered.

In the contour plot given by Figure 6, we present the line intensity ratio \((i+j)/r\) of Al XII as functions of electron and neutral densities by using the hybrid model in collisions with H, He, H2O, and O. Collisions with CO, CO2, and H2 show an almost identical density dependence to that with H2O and are not presented here. At the same electron and neutral density ranges illustrated in the plots, the collision with H atoms will give a wider range (see color bar labels) for the line intensity ratio, that is, the line intensity ratio is higher in collisions with H atoms than in collisions with other targets at given electron and neutral densities. For the experimental line ratio \(0.92 ± 0.05\) at a distance of 4.0 mm, the range of electron density (solid lines; \((5.5–9.5) \times 10^{19} \text{ cm}^{-3}\)) from the collision with H atoms is obviously higher than that in the collisions with other targets. The collisions with H2O, CO, CO2, and H2 basically give a comparable range of electron density \((2.0–4.5) \times 10^{19} \text{ cm}^{-3}\).

By consideration of the outflow density \((2–3.5) \times 10^{19} \text{ cm}^{-3}\), the electron density at the interaction zone (post-shock) will be \(~3\) times that before collisions (Dizière et al. 2015). Assuming an electron density of \((6.0–10.0) \times 10^{19} \text{ cm}^{-3}\) at the interaction zone is acceptable. The above subsection and Figure 6 demonstrate that the line ratio is insensitive to neutral density above \(10^{16} \text{ cm}^{-3}\). Then, a neutral density of \(10^{18}–10^{19} \text{ cm}^{-3}\) is assumed at the interaction zone, but with a large uncertainty due to the absence of a good diagnostic method. From the contour plot in Figure 6 and Figure 8, we can see that the high line intensity ratio of \(0.92 ± 0.05\) at a distance of 4.0 mm can be explained by the present hybrid model with electron capture from hydrogen or oxygen atoms. Since oxygen has a similar open-shell structure to carbon as mentioned above, carbon atoms may be the dominant donor for charge exchange. At a short collisional distance of 3.2 mm, a lower line intensity ratio of \(0.69 ± 0.07\) can be explained by the present hybrid model with electron capture from H2O, CO, CO2, H2, and He, where charge exchange may be dominated by singly charged carbon ions (C+) with ionization potential of 24.37 eV, which is
In conclusion, we believe that charge-exchange processes are necessary for the understanding of X-ray emissions at the interaction zone of hot outflow impinging on a cold medium, though the absence of a reliable neutral density and an estimation of the electron density is used here for discussion purposes.

4.4. Length Scale and Its Comparison to the Cap of M82 and HH 248

According to the brightness in X-ray morphology from pinhole cameras, we derive the length scale of the X-ray-emitting region along the axial outflow in this experimental interaction zone; see Table 1. In the collision with the CH obstacle at a distance of ∼1.6 mm (Liang et al. 2018, Figure 2), the length scale of the interaction zone is ∼160 μm, which is consistent with our previous hydrodynamic FLASH simulation (∼120 μm thickness with high temperature of ≥100 eV and electron density of ∼10^{19} cm^{-3}) with a designed distance of 2.0 mm between Al target and CH obstacle. In the collisions at the distance of 3.3–4.0 mm presented in Figure 2 of this paper, the length scale of the X-ray-emitting region is ∼420–490 μm. This agrees well with the results from Dizièré et al. (2015) by using self-X-ray emissions in their outflow interaction with nitrogen (N₂) gas. By optical shadowgraphy, Nicolai et al. (2008) obtained a thickness between bow shock and Mach disk of ∼500–850 μm at high gas pressure. This is slightly larger than our experimental one, where the length scale represents the thickness between the contact discontinuity and Mach disk as shown in Figure 2.

Although the measured spectra are integrated in temporal and spatial dimensions, the line intensity ratio is determined by the competitive level populations from electron collisions and charge exchanges as shown in Figure 5, which can provide insight into the length scale for the charge exchange. As mentioned in the above subsection, neutral density is not diagnosed, which is antiproportional to the length scale of the interaction zone; see Table 1. In the collision with H, the length scale is

$$\ell = \frac{n_e}{\sigma_{cx}}$$

which is estimated from the broken solid line at low- and high-limit neutral densities (corresponding to the experimental ratio of 0.92) in Figure 6. White plus signs refer to the electron temperature (416 eV) and outflow velocity (330 km s^{-1}) diagnosed from other methods (Liang et al. 2018) and used in Figure 6.

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4.4. Length Scale and Its Comparison to the Cap of M82 and HH 248

According to the brightness in X-ray morphology from pinhole cameras, we derive the length scale of the X-ray-emitting region along the axial outflow in this experimental interaction zone; see Table 1. In the collision with the CH obstacle at a distance of ∼1.6 mm (Liang et al. 2018, Figure 2), the length scale of the interaction zone is ∼160 μm, which is consistent with our previous hydrodynamic FLASH simulation (∼120 μm thickness with high temperature of ≥100 eV and electron density of ∼10^{19} cm^{-3}) with a designed distance of 2.0 mm between Al target and CH obstacle. In the collisions at the distance of 3.3–4.0 mm presented in Figure 2 of this paper, the length scale of the X-ray-emitting region is ∼420–490 μm. This agrees well with the results from Dizièré et al. (2015) by using self-X-ray emissions in their outflow interaction with nitrogen (N₂) gas. By optical shadowgraphy, Nicolai et al. (2008) obtained a thickness between bow shock and Mach disk of ∼500–850 μm at high gas pressure. This is slightly larger than our experimental one, where the length scale represents the thickness between the contact discontinuity and Mach disk as shown in Figure 2.

Although the measured spectra are integrated in temporal and spatial dimensions, the line intensity ratio is determined by the competitive level populations from electron collisions and charge exchanges as shown in Figure 5, which can provide insight into the length scale for the charge exchange. As mentioned in the above subsection, neutral density is not diagnosed, which is antiproportional to the length scale (ℓ) as

$$\ell \approx \frac{1}{n_{\text{ion}} \sigma_{\text{cx}}}$$

Then, we replotted the top left panel of Figure 6 (collision with H) by changing neutral density to length scale ℓ, as shown in Figure 9. According to the estimated electron density of ∼8.0 × 10^{19} cm^{-3} in the interaction region and the experimental ratio of 0.92 ± 0.05, the length scale is
deduced to be $\sim 40 \mu m$ for the charge exchange. This implies a dimensionless ratio ($\kappa_{lab} = \ell_{cx}/\ell_{X-ray}$) of $\sim 0.1$ for length scales between the charge-exchange region and the X-ray-emitting region in our laboratory interaction zone. For other previous laboratory measurements as listed in Table 1, there are no high-resolution spectra available to examine the length scale of charge exchange.

Here we select the Cap region near starburst galaxy M82 and HH 248 as astrophysical interaction scenarios for the comparison to our laboratory analog.

By X-ray imaging observation for the starburst galaxy M82 with Suzaku and XMM-Newton satellites, Tsuru et al. (2007) found an extended X-ray emission from the Cap region, located at 11$''$ (11.6 kpc) above the disk of M82. The length scale of the diffuse X-ray region is about 0.9 kpc in the outflow direction. Analyses of metal abundance revealed that the diffuse X-ray emissions are from explosions occurring in the starburst M82 galaxy. The observed line fluxes at 0.46 and 0.57 keV were suggested to be charge-exchange processes of superwinds with the galaxy. The observed line fluxes are from explosions occurring in the starburst M82 galaxy. The observed line fluxes at 0.46 and 0.57 keV were suggested to be charge-exchange processes of superwinds with the galaxy. High-resolution reflection grating spectrometer spectroscopy observed with the XMM-Newton satellite, the charge-exchange process has been confirmed by Zhang et al. (2014) and contributes a quarter of observed lines fluxes. From triplets of O VII, Liu et al. (2011, 2012) estimated that the CX contribution occupies about 80%. The density of the H I cloud around the Cap was obtained to be $\lesssim 2.0 \times 10^{-3} \text{ cm}^{-3}$ (Yun et al. 1993). Then, we derive the length scale for charge exchange to be $1/(\tau_{IC} \sigma_{cx}) \sim 0.1 \text{ pc}$, where charge-exchange cross section of H-like oxygen collision with H atoms is deduced from the fitting parameters of Gu et al. (2015), $\sigma_{cx} = 5.2 \times 10^{-15} \text{ cm}^2$ at the relative velocity of $\sim 500 \text{ km s}^{-1}$ (Zhang et al. 2014). The dimensionless ratio of length scale is $\kappa_{M82} \sim 10^{-2}$, which is far smaller than that ($\kappa_{lab} \sim 0.1$) in our laboratory analog. According to the principle of Euler similarity (Ryutov et al. 1999, 2000), the dimensionless ratio of length scale can be compared directly without scaling. This large difference is probably because of the difference of the outflow velocities ($330 \text{ km s}^{-1}$ in our laboratory and $\gtrsim 1000 \text{ km s}^{-1}$ in M82) and the density ratio between outflow and ambient gas in the two different cases. In our laboratory collision, the density ratio $\eta = \rho_{outflow}/\rho_{gas}$ is $\sim 0.1-0.5$ (Liang et al. 2018). Zhang et al. (2014) estimated the outflow density to be $\sim 0.05 \text{ cm}^{-3}$. The density ratio $\eta$ around the Cap region is $\sim 25$.

Using a hybrid model for O VII, we plot a similar contour plot for line intensity ratio $f/r$ as in Al XII; see the right panel of Figure 9. Here the electron temperature (0.6 keV), cloud density ($2.0 \times 10^{-3} \text{ cm}^{-3}$) at the Cap, and relative collision velocity ($500 \text{ km s}^{-1}$) in M82 are from the works of Yun et al. (1993) and Zhang et al. (2014). The atomic data source is basically the same as Al XII as discussed in Section 3. According to the theory of shock physics (Hartigan 1989) and some experiments (Dizière et al. 2015), the electron density at the Cap region will be $\sim 3$ times that in outflows ($0.05 \text{ cm}^{-3}$). Then, the length scale of charge exchange is estimated to be $\sim 0.4 \text{ pc}$ in the Cap of M82, which agrees with the above estimation from the H I cloud density within an order of magnitude. This means that the spectroscopic method for the estimation of CX length scales is feasible.

López-Santiago et al. (2015) suggested that the extended X-ray emission ($\sim 9$") at decl./R.A. $= -02^\circ 23'02''/05^\circ 41'25''$ near CTTS V615 Ori is the jet in HH 248 colliding on the Horsehead Nebula. Here we adopt similar values for the densities of the jet ($\sim 500 \text{ cm}^{-3}$) and molecular cloud ($\sim 5000 \text{ cm}^{-3}$) to those in López-Santiago et al. (2015) and Liang et al. (2018). Caballero (2008) deduced the distance of $\sigma$ Orionis to be $\sim 350-450 \text{ pc}$. Then, the length scale of the extended X-ray source is deduced to be $\sim 310-400 \text{ au}$. The hydrodynamic simulation performed by López-Santiago et al. (2015) indicates that the jet velocity in HH 248 is $\gtrsim 700 \text{ km s}^{-1}$. The charge-exchange cross section of H-like oxygen will be less than $5.3 \times 10^{-15} \text{ cm}^2$. Then, the length scale is deduced to be $\sim 0.002 \text{ au}$ for the charge exchange. The dimensionless ratio of length scale is $\kappa_{HH 248} \sim 10^{-5}$, being still far smaller than this experimental value. Yet the density ratio $\eta \sim 0.1$ is comparable to that in this experiment. So the density ratio is not an important factor on emission structure of X-ray morphology, but the outflow velocity may be a significant factor.

In summary, collision experiments can be used to simulate some astrophysical interaction scenarios (Liang et al. 2018). The rough discussions reveal an obvious difference of emission structure in X-ray morphology for the two cases. This indicates that there are still more efforts required to determine fundamental parameters accurately for the physics of collision dynamics in the starburst galaxy M82 or HH 248 and in our experiments. In M82 and HH 248, outflow velocities are estimated from hydrodynamic simulations, outflow density is estimated from global fitting, and cone-shape geometry is assumed (Zhang et al. 2014), and only the upper limit can be available for the density of ambient gas. This provides insight into the requirements for observations with imaging spectroscopy with high energy and spatial resolutions, e.g., Athena13 and

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**Table 1**

| X-Ray Region (\(\mu m\)) | CX Region (\(\mu m\)) | References |
|---------------------------|-----------------------|------------|
| Collision with CH/exp     | $\sim 420-490$        | $\sim 40$  | This work (3.3–4.0 mm) |
| Collision with CH/exp     | $\sim 160$            |            | Liang et al. (2018, 1.6 mm) |
| FLASH simulation          | $\sim 120$            |            | Liang et al. (2018, 2.0 mm) |
| Collision with Ar gas/exp.| $\sim 500-850^*$      |            | Nicolai et al. (2008) |
| Collision with N$_2$ gas/exp.| $\sim 500-750$      |            | Diziere et al. (2015) |
| Cap of M82                | $\sim 0.9 \text{ kpc}$| $\sim 0.1 \text{ pc}$ | Tsuru et al. (2007), Zhang et al. (2014) |
| HH 248                    | $\sim 310-400 \text{ au}$ | $\gtrsim 0.002 \text{ au}$ | López-Santiago et al. (2015), Liang et al. (2018) |

Notes.

$^*$ Thickness between bow shock and Mach disk is adopted here from Nicolai et al. (2008).

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13 https://www.cosmos.esa.int/web/athena
HUBS.\textsuperscript{14} In our experiments, a method is necessary to define the neutral density in such experiments. The transient properties of laser-produced outflow will result in large gradients in densities and temperatures that will be transferred to integrated spectra and further the estimation of length scale for the charge exchange.

5. Summary and Conclusion

In this paper, we report a laboratory outflow with a velocity of 330 km s\(^{-1}\) impacting on a cold medium, where we observe a similar bow-shape contact discontinuity and Mach disk to the interaction model of Hartigan (1989). A hybrid atomic model was set up by including the electron impact excitation and charge-exchange cross section from the Kronos v3.1 database (see footnote 1) with different neutrals. The combination of electron excitation and charge exchange can explain the experimental spectra with measured line intensity ratio \((i+j)/r\) of 0.65–0.95. That is, nonthermal charge-exchange emission was detected in high-resolution spectroscopy of laboratory supersonic outflow interaction with the cold medium.

We also explore the effects from multiple-electron targets on the line intensity ratio \((i+j)/r\), as well as its density (\(n_e, \kappa_{\text{neutral}}\)), temperature, and velocity dependence by contour plots. The difference is very obvious in collisions with different targets at the high-density laser plasma as in the pure CXE model given by Mullen et al. (2017). We found that the ratio is insensitive to neutral density above \(10^{16}\) cm\(^{-3}\). According to the diagnosed electron density of outflow in this experiment (Liang et al. 2018), we estimated the electron density to be \((6.0-10.0) \times 10^{19}\) cm\(^{-3}\) at the interaction zone. According to the agreement between experimental measurements and hybrid predictions with different targets, we suggest that collisions with H and/or carbon atoms will dominate charge exchange at longer distances, whereas collisions with singly charged ions (C\(^{+}\)) will dominate charge exchange at short distances.

Length scales of X-ray-emitting and charge-exchange regions at the interaction zone are estimated to be about \(\sim 420-490\) m and \(\sim 40\) \(\mu\)m, respectively. The dimensionless ratio of length scales \(\kappa_{\text{lab}} = l_{\text{cx}}/l_{\text{X-rays}}\) is estimated to be \(\sim 0.1\) in our laboratory measurement. For the Cap region in starburst galaxy M82 and HH 248, the dimensionless ratio is \(\sim 10^{-5}-10^{-4}\). The obvious difference of emission structure in X-ray morphology is probably due to the differences in outflow velocities and the large uncertainties of parameters for the laboratory analog and the Cap region in M82 or HH 248. High \(\sim 25\) in Cap of M82) and low \(\sim 0.1\) in HH 248) density ratios indicate that its role on the emission structure in X-ray morphology can be excluded.

In conclusion, we believe that the charge-exchange process take places in our laboratory analog to astrophysical outflow interactions with surrounding cool gases (e.g., the outflow Cap of M82; Zhang et al. 2014) or infall interaction with stellar surface in YSOs. However, we have to remind that theoretical charge-exchange cross sections with different neutrals are used in this work. There are still more elaborated works to benchmark the charge-exchange spectroscopy for its applications in X-ray astronomy and such kinds of laboratory analogs.

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