New 8-Color, Spectrally-Resolved, Pathlength-Amplified Absorption Spectroscopy Measurements of Air-Argon-XenonPlasmas Behind Reflected Shock Waves

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Background

The validation of new collisional-radiative models for the excitation and ionization of air requires quantitative measurements of the different excited and ionized species present in re-entry and hypersonic-relevant flows. Such measurements behind shock waves have been difficult, owing to the rapid timescales of the formation and decomposition of excited atoms, molecules, and ions, as well as their low concentrations. Previous works have shown that using recently developed pathlength amplification technology for reflected shock tubes, such measurements are possible for some key excited states of oxygen and nitrogen, as well as electron number density from the Stark shift and broadening of a high-lying argon state, a common bath gas used in reflected shock tube experiments[1,2,3]. These early experiments identified large discrepancies between existing collisional-radiative models and experimental measurements of O and N excited states on the order of 3x, while the Ar excited state populations were well-predicted. Models likewise overpredicted the late-time electron number densities by a factor of 2[4]. Unfortunately, these measurements captured only a small fraction of the important excited atomic states present in such flows and entirely neglected the molecular excited states[5].

This work presents new measurements of three excited states of O, three excited states of N, two excited states of Ar, NO(A), N_2(A), N_2^+(X), six states of Xe including the first excited state, along with multiple measurements of the translational temperature, electron number density, and

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[1] Merrell, Devin, et al. (2025) DOI: 10.2514/6.2025-1995

[2] Strand, Christopher L., et al. (2025) DOI: 10.1364/OE.571994

[3] Merrell, Devin P., et al. (2026) DOI: 10.1016/j.jqsrt.2026.110005

[4] Merrell, Devin, et al. (2026) DOI: 10.2514/6.2026-2265

[5] Aiken, Timothy T., Iain D. Boyd, and Igor V. Adamovich. (2025) DOI: 10.1063/5.0294530

electron temperature across multiple mixtures of $O_2/N_2/Ar/Xe$. Up to ten of these species were measured simultaneously, with measurements depending on the mixture and temperature regime.

Methodology

Pathlength-amplified, spectrally-resolved laser absorption spectroscopy enabled the capture of time histories in each shock tube experiment, with vibrationally-frozen post-reflected-shock temperatures ranging from 8500 K to 15000 K in $O_2/N_2/Ar$, 8500 K to 25000 K in $O_2/N_2/Xe$, and up to 50000 K in pure xenon. Pressures varied between 0.03 atm and 2 atm, with the vast majority of experiments conducted below 0.5 atm. Eight different lasers were deployed simultaneously in each experiment, capturing different regions of the NIR spectrum. Six of these lasers operated over a narrow range of 1-2 cm^{-1} allowing for the detailed capture of absorption lineshapes for both atomic and molecular lines, all while sampling at rates between 500 kHz and 1 MHz. A seventh laser system, a MEMS VCSEL centered at 1060 nm produced by Thorlabs allowed for the sampling of the entire 1 – 1.1 um region, capturing 900 cm^{-1} of spectra at up to 400 kHz. An eighth and final laser system, a tunable Coherent Chameleon laser, produced broadband laser light at 811 nm which was spectrally resolved using a 3-meter spectrometer to capture the first excited state of argon. All lasers passed through a Stanford reflected shock tube 5 mm away from the endwall, minimizing non-ideal shock tube effects encountered at high temperatures.

Results

Time histories were successfully collected in over 120 experiments, a subset of which will be presented. NO(A) measurements showed the rapid evolution of the number density in time, capturing the rise, peak, and decay of the population. $N_2(A)$ was observed to have a similar rise time in air mixtures where both NO(A) and $N_2(A)$ were present, forming much faster than in N_2-Ar mixtures. $N_2(A)$ was always observed with a much slower decay than the NO(A) population, likely due to the much more rapid dissociation of NO than N_2. N_2^+ exhibited a very slow formation and removal time, lasting much longer than either NO(A) or $N_2(A)$. Neighboring atomic states were observed to be in near-equilibrium with each other, with high-lying and strongly radiating states being relatively depleted over low-lying states with no strong radiation pathways. Electrons were observed to form on the atomic excitation timescale.

Conclusion

This new expansive dataset will enable the validation and improvement of collisional-radiative models for the excitation and ionization of air through a collaboration with the University of Colorado Boulder.