Self-organized criticality and prethermalization in the nitric oxide molecular ultracold plasma

A. Allahverdian,[1] ***R. Wang,***[2] ***S. Colombini,***[1] ***N. Durand-Brousseau,***[1,2] ***K. Marroquín,***[1] ***J. Keller,***[3] ***J. Sous,***[4] ***A. Prem,***[5] ***E. Grant****[1,2]

[1]Department of Chemistry, University of British Columbia, Vancouver, BC V6T 1Z1, Canada
[2]Department of Physics & Astronomy, University of British Columbia, Vancouver, BC V6T 1Z3, Canada
[3]Department of Chemistry, Kenyon College, Gambier, OH 43022 USA
[4]Department of Applied Physics, Yale University, New Haven, CT 06516 USA
[5]School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540, USA

(*) ed.grant@ubc.ca

Prethermalization occurs as a state of quasi-equilibrium when an energetic or dynamic gap confines an isolated many-body system to a subspace separated from thermodynamic equilibrium. Constrained relaxation in a prethermal phase can support restricted mobility in natural and model systems of high dimensionality and limited disorder. Here, we describe the signature of an enduring prethermal regime of arrested relaxation in the molecular ultracold plasma that forms following the avalanche of a state-selected Rydberg gas of nitric oxide. This robust final state, consisting of weakly associated nitric oxide ions and electrons, persists on a millisecond timescale despite accessible dissociation channels to neutral atoms. In every realization, ionization avalanches mark the initial progress to this state by a power-law size distribution that suggests an intermediate regime of self-organized critical (SOC).

For a wide range of initial conditions, this system forms an evolving phase in which a substantial density of NO^+ and electrons balances a population of Rydberg molecules. Electron collisions mix orbital angular momentum, scattering Rydberg molecules to states of very high-ℓ. Low-ℓ states rapidly predissociate, purifying this non-penetrating character, creating an extraordinary gap between the plasma states of $n \approx \ell$, with measured $n > 200$ and penetrating states of $\ell = 0,\ 1$ and 2. Evolution to a statistically equilibrated state of N and O atoms cannot occur without Rydberg electron penetration, and this gap blocks relaxation for a millisecond or more.

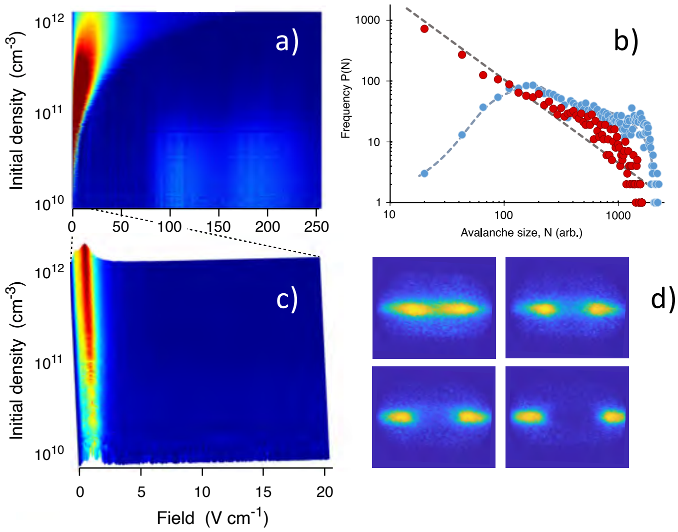

Figure 1: a) Selective field ionization spectrum of the evolving NO plasma in a power-law regime of avalanche size, b). c) Field ionization spectrum of the prethermalized state, in which no electron is bound by more than 10 cm^{-1} and the plasma bifurcates to form prethermalized volumes, d).

We find that a set of coarse-grained rate laws describing electron impact ionization, recombination and neutral dissipation processes conforms with the attractor observed experimentally. The stochastic implementation of these rate processes in a percolation model captures the transition to a critical state, replicating the attractor and power-law characteristics of this system. Evolving through the critical regime, electrons that balance the NO^+ charge behave as though localized in the prethermal phase and play an ineffective role in bridging this gap. However, ℓ-mixng, driven by mm-wave Rydberg-Rydberg transitions to penetrating states or weak radiofrequency field (RF) induced electron-Rydberg collisions, bridges the angular momentum gap, causing the entire ensemble to thermalize. The molecular nitric oxide ultracold plasma offers a novel experimental and theoretical platform in which a quantitative reference to microscopic dynamics accounts for the spontaneous formation of an emergent SOC ensemble that evolves to a sub-critical prethermalized state.

References: R. Wang, et al. *Phys Rev Research* (2025), in press; K Marroquín et al. *J Plasma Phys* (2024) **90**:935900101; R. Wang, et al. *J Chem Phys* (2022) **157**:064305; R. Wang, et al. *Phys Rev A* (2020) **102**:063122.