Evolution dynamics of a molecular Rydberg gas to ultracold plasma

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Laboratory studies of strongly coupled plasmas provide a means to probe the dynamics of many-body processes that relate to a broad range of exotic but important charged-particle systems. Because classical Coulomb dynamics scale, the properties of strongly coupled systems at low density connect directly to a very diverse range of phenomena from the evolution of stars and planets to low-temperature charge transport in complex materials. Energetic plasmas become strongly coupled at extremely high densities, when the average distance between ions, a_{ws}, nears the Bohr radius. Ultracold plasmas approach states of strong coupling ($\Gamma = e^2/4\pi\epsilon_0 a_{ws} k_B T > 1$) by virtue of their low temperatures. Created from ultracold atoms held in a magneto-optical trap (MOT), or molecules seeded at higher density in a supersonic expansion, plasmas with ion temperatures, T_i, of 1 K can reach Γ_i from 3 to nearly 30. Strongly coupled ultracold plasmas manifest liquidlike or even crystalline properties. But, interparticle forces arising from strong coupling cause disorder-induced or correlation heating, which acts intrinsically to limit the development of strong coupling as a dense but randomly ordered Rydberg gas evolves to a plasma. Precorrelating the excited gas offers one means to overcome this limitation. For example, dipole blockade forms strong correlations in the spatial positions of Rydberg atoms created by narrow-band laser excitation, and recent models have suggested that the ionization of a blockaded Rydberg gas can reduce disorder-induced heating.

We have found an alternate, highly robust method for the introduction of spatial correlations. This method exploits a process occurring naturally in the evolution from a molecular Rydberg gas of nitric oxide to an ultracold plasma. Recognizing the spatial selectivity of Penning ionization, we develop a model, supported by experimental results, that defines conditions for the formation of a lattice-like spatial distribution of ions, which leads to a state of ion correlation that observably affects the free space expansion of the plasma.

We have also studied the effects of the collision of plasma volumes. Such interactions can produce charge density and velocity discontinuities that create highly nonlinear electrostatic force gradients. These gradients accelerate electrons to produce soliton-like shock fronts. Such features created at high energy and density have attracted interest as bright sources of accelerated electrons and high-energy radiation. We report the development of a low-density simulator using down-stream laser excitation to create a second plasma that proceeds to expand within an existing molecular beam ultracold plasma. We find that formation of a secondary plasma of NO^+ ions and electrons in the core of an ultracold molecular plasma cooled by ambipolar expansion changes the hydrodynamics of the system. When this process adds energetic electrons by photoionization, the rate of expansion increases. Introducing instead a secondary Rydberg gas slightly diminishes the terminal velocity of the plasma ions. In both cases, we see an interval of time during which the inertial drag of the cold secondary ions retards the thermal expansion of the electron gas. We can explain these effects in terms of a cold-ion shell model for the ambipolar hydrodynamics. This model accounts well for the overall effect of energy added by photoionization electrons. The model also predicts the formation of collisionless shock waves.

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