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Heating and collective effects in ultracold plasmas

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Ultracold plasma (UCP) is a low temperature (a few K) and classical plasma with their average kinetic energy of charged particles comparable or less than the average inter-particle potential energy of charged particles. This property (known as strong coupling effects) makes it an interesting testbed to validate theories of strongly coupled plasmas with the help of table-top UCP experiments. Such validated theoretical models and understanding of strongly coupled plasmas can then be employed to explain phenomena in high energy density plasmas which are otherwise challenging to get examine experimentally due to their extreme temperature and density.

Recombination and heating are two dominant processes in an ultracold plasma during its evolution. Recombination causes the formation of bound Rydberg atoms along with the free charge species. This co-existence of free and bound charges affects the dynamical processes and depend strongly on the concentration of bound charges in the plasma at any given moment. Heating is an outcome of recombination (as well as the disorder) and limits in attaining higher coupling strength for UCPs. Reduction of heating is a topic of immediate interest to help improve the coupling strength of UCPs.

To understand processes of recombination and heating, we proposed a model for simulating ultracold neutral plasmas using classical molecular dynamics simulations (Sanat Kumar Tiwari et al., Phys Rev E **95**, 043204, 2017). An electron-ion system is prepared where charged particles interact through long-ranged Coulomb potential. To avoid the Coulomb collapse of oppositely charged species, an artificial repulsive core was used along with the Coulomb potential. Depending upon the length-scale of the repulsive core (i.e. the depth of the potential well formed between oppositely charged particles), charged particles form classical bound states of different energy level (i.e. paired, chain-like, ring-like structures of electrons and ions). It was also found that the concentration of bound charges can be controlled by the choice of the repulsive core scale length. These bound states could be seen as the classical Rydberg states observed in a typical UCP experiment (R. S. Fletcher et al., Phys. Rev. Lett. **99**, 145001, 2007). The model was first employed to calculate the thermodynamic state variables, pressure and internal energy, in a recombining UCP (at fixed conditions). We devised a model to separate the contribution of free and bound charges from the Radial Distribution Functions (RDF) and hence calculating the partial excess pressure and partial internal energies of plasma (i.e. free charges) and neutrals (i.e. bound Rydberg atoms). We reported that the total pressure of the system was found to be positive while the partial excess pressure due to plasma was found to contribute negative (Sanat Kumar Tiwari et al., Phys Rev E **95**, 043204, 2017). It was found that the excess pressure and excess internal energy of the free charges become independent of the choice of repulsive core length scale length when it is sufficiently short-ranged. The same simulation model has also been used to validate best suited Ornstein-Zernike/Hypernetted chain model to calculate pair-correlation functions for two temperature plasmas (Nathaniel R. Shaffer et al., Physics of Plasmas **24**, 092703, 2017).

In this paper, we will discuss how the recombination changes the dynamic properties and how can the heating can be reduced to get improved coupling strength of UCPs. While answering the first, we will see changes in static structure and dynamical structure factors along with auto-correlation functions as the recombination rate increases and its effect on the sound speed in the medium. We explore the possibility of existence/non-existence of novel modes due to the presence of different forms of bound states in UCP. While answering explaining the second point, we will see the reduction in heating effects as a strong magnetic field is applied externally and its effect on other particle properties (Sanat Kumar Tiwari et al., Physics of Plasmas **25**, 013511, 2018).