§17. Development of Improved Collision Operator for Multi-species Plasma Kinetic Simulations

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Understanding transport processes of particle, momentum, and energy in magnetically confined plasmas is a central issue in fusion plasma research, and transport levels driven by turbulent electromagnetic fields are, in general, much higher than the neoclassical (or collisional) ones in the core region, where the so-called gyrokinetic model is a powerful tool for both analytic and numerical studies of such core turbulent transport. Especially, turbulent transport of fuel ions (Deuterium: D and Tritium: T) and several light/heavy impurities, e.g., thermalized Helium(He) ions produced by fusion reaction, is of particular importance on the feasibility of self-ignited steady state and on the optimization of the burning efficiency in future fusion device. Development of the multi-species gyrokinetic turbulence simulations including the like-particle and unlike-particle collisions is thus indispensable.

Recently, Sugama et al., derived a precise linearized collision operator which preserves both the conservation properties and the self-adjointness (or the Boltzmann's H-theorem) for arbitrary multi-species ions and electrons[1]. The new collision operator has been implemented to a gyrokinetic Eulerian code GKV, and the conservation and self-adjointness properties are successfully verified for the multi-ion species system[2], where the collisional interaction with kinetic electrons was ignored there.

In this study, an improved collision operator has been newly developed based on the original form of the Sugama's operator, and its numerical accuracy is verified for kinetic simulations composed of both multi-species ions and electrons[3]. It is confirmed that all the conservation properties on the implemented collision operator are accurately satisfied within the round-off error level. We also found that the collisional relaxation of thermal fluctuations is successfully solved for the system composed of D, T, and He with electrons [Fig. 1], and their distribution functions are relaxed towards an equilibrium distribution [Fig. 2], i.e., the perturbed Maxwellian. The conservation accuracy of round-off error levels is then sustained for sufficiently long time. It is also revealed that the improved collision operator preserves the Boltzmann's H-theorem for the multi-species ions and electrons system [Fig. 3], i.e., the collisional entropy production rate is positive definite in the thermal relaxation process.

The self-adjoint multi-species collision operator and its numerical improvement ensuring conservation properties shown in this study can be applied not only for fusion plasmas, but also for general laboratory- and space-plasmas composed of multi-species ions and electrons. More practical analyses such as kinetic turbulence or neoclassical simulations will be addressed in our future works.

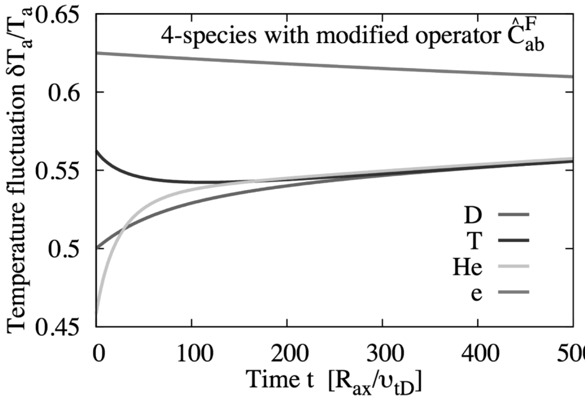

Fig. 1: Collisional relaxation of thermal fluctuations with the improved multi-species collision operator.

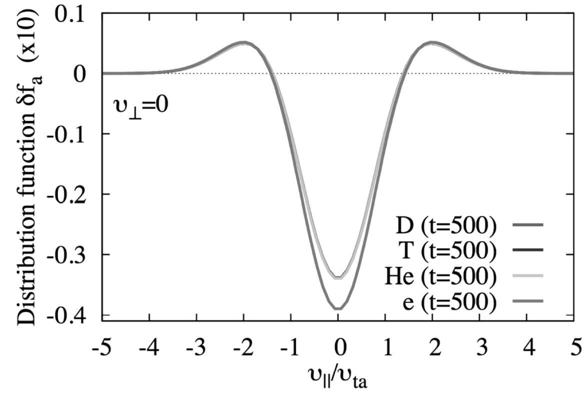

Fig. 2: Velocity-space structure of the perturbed distribution function of each species at t=500[R_{ax}/v_{tD}].

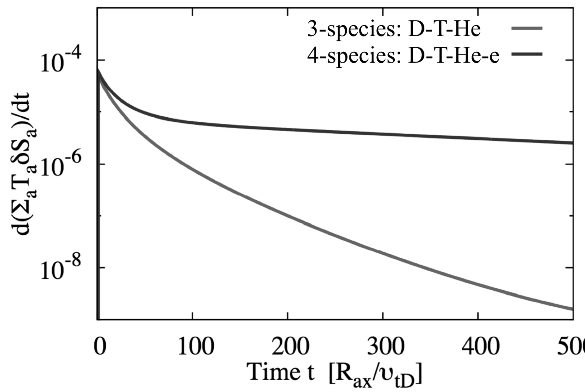

Fig. 3: Time evolution of the collisional entropy production rate (should be positive definite) in the thermal relaxation processes for 3- and 4-species systems.

1) Sugama, H. et al.: Phys. Plasmas **16** (2009) 112503.
2) Nunami, M. et al.: Plasma Fusion Res. **10** (2015) 1403058.
3) Nakata, M. et al.: Comput. Phys. Comm., submitted