Constraining supernova equations of state

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Cluster formation is a fundamental aspect of the equation of state (EOS) of warm nuclear matter such as can be found in supernovae (SNe). Similar matter, with properties comparable to that found in the neutrinosphere region of a supernova, can be studied in heavy-ion collisions (HIC). We have used the experimental data of Qin *et al.*[1] to test calculations of cluster formation and the role of in-medium modifications of cluster properties in SN EOSs. For the comparison between theory and experiment we use chemical equilibrium constants as the main observables. This reduces some of the systematic uncertainties and allows deviations from ideal gas behavior to be identified clearly. In the analysis, we carefully account for the differences between matter in SNe and HICs. At the lowest densities, the experimental data and all

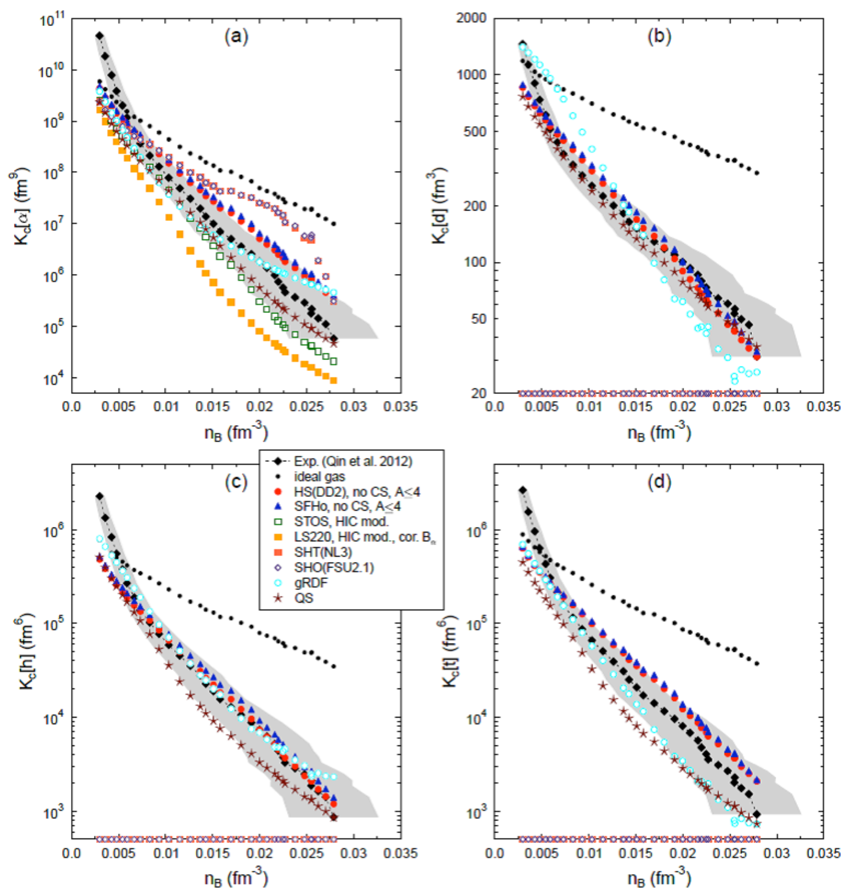

FIG. 1. Equilibrium constants vs density. ECs for (a) α particles, (b) deuterons, (c) helions, and (d) tritons from the experiments (black diamonds) are compared with those from various theoretical models, which are all adapted for the conditions in HIC, as far as possible. The ECs of nuclei which are not included in a specific model are put on the x axis.

theoretical models are consistent with ideal gas behavior. See Fig. 1.

Equilibrium constants should only be independent of composition, density, and asymmetry for ideal Maxwell-Boltzmann gases without interactions. In that case they are only a function of temperature. Fig. 2 presents the equilibrium constants as a function of temperature. As soon as interactions and/or Fermi-Dirac or Bose-Einstein statistics are included, a dependence on composition and density arises. Deviations of ECs from the ideal values measure the strength of interactions. Thus ECs represent very useful and instructive quantities. Furthermore, some of the systematic uncertainties are reduced when one uses ECs instead of particle yields or mass fractions. ECs will depend on the asymmetry of the system, or, equivalently, the total proton fraction Ytot p. Therefore we chose YTot p= 0.41, as determined in the experiments, for all theoretical calculations.

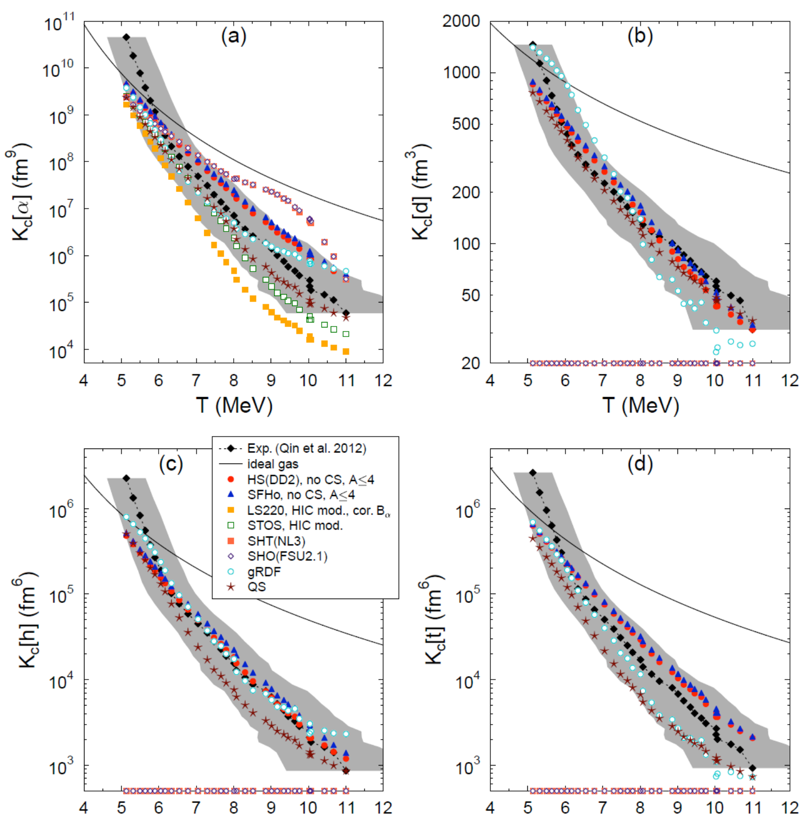

FIG. 2. Equilibrium constants vs temperature. This figure shows the main results of our investigation: EC for (a) alpha particles, (b) deuterons,(c) helions, and (d) tritons as a function of temperature. The grey band represents the experimental uncertainty for the temperature determinations. Experimental data (black diamonds) is compared with various different theoretical models, which are all adapted for the conditions in HIC, as far as possible. The ECs of nuclei which are not included in a model are put on the x-axis. The black lines show the ECs of the ideal gas model, which are solely a function of temperature.

Four of the models which we considered (QS, gRDF, HS(DD2), SFHo) are fully compatible with the experimental data, or show at least only minor deviations from the experiment. We conclude that at the densities and temperatures discussed mean-field interactions of nucleons, inclusion of all relevant light clusters, and a suppression mechanism of clusters at high densities have to be incorporated in the SN EOS. From the comparison with the models that fail to explain the full experimental data set, we can identify the following three ingredients that seem to be necessary for the description of clusterized nuclear matter at the densities and temperatures of interest: (i) consideration of all relevant particle degrees of freedom, (ii)mean-field effects of the unbound nucleons, and (iii) a suppression mechanism for bound clusters at high densities.

[1] L.-J. Qin *et al.*, Phys. Rev. Lett. **108**, 172701 (2012).