Binding energy shift of the light clusters in warm stellar matter from heavy-ion reactions

S. Mallik[1],* H. Pais[2], and F. Gulminelli[3]
[1] *Physics Group, Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Kolkata 700 064, India*
[2] *CFisUC, Department of Physics, University of Coimbra, 3004-516 Coimbra, Portugal and*
[3] *Normandie Univ., ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, F-14000 Caen, France*

Light clusters such as Hydrogen and Helium isotopes are expected to be copiously produced in the thermodynamic conditions corresponding to supernova matter and neutron star mergers [1]. However the properties of the light clusters are modified in the dense matter, therefore the study of the in-medium effects is an active area of research in nuclear physics. A density dependent binding energy shift for the light clusters can be introduced with the help of experimental constraints for heavy ion reactions, where such clusters are abundantly produced, though in transient configuration.

In stead of using cluster yields directly, a useful observable to pin down the in-medium effects from heavy-ion collisions is chemical equilibrium constant [2]. In a well-defined thermodynamic equilibrium condition characterized by the temperature T, total baryonic density n_B and proton fraction y_p , the equilibrium chemical constant $K_c(A, Z)$ of a cluster of mass number A and atomic number Z can be defined as

$$K_c(A, Z) = \frac{n_{AZ}}{n_{g,p}^{Z} n_{g,n}^{A-Z}}, \qquad (1)$$

where n_{AZ}, $n_{g,p}$ and $n_{g,n}$ are the densities of the specific cluster of mass A and charge Z, free protons and free neutrons respectively. Recently, $K_c(A, Z)$ for Hydrogen and Helium isotopes for different surface velocity bins were measured by INDRA collaboration in ^{124}Xe on ^{124}Sn central collision reaction at 32 AMeV [3, 4]. The thermodynamic variables (T, n_B, y_p) were extracted from the experimentally measured multiplicities for each surface velocity bin by allowing the arbitrary deviations from the ideal gas limit with the constraint condition of a common volume for the different particle species. For the present work, the experimentally measured thermodynamic variables (T, n_B, y_p) are used at the input of the nuclear statistical equilibrium (NSE) model [5]. According to this NSE model, the abundance of the free nucleon gas as well as various clusters are determined from the phase space calculation in the grand-canonical ensemble and the cluster functionals are determined from metamodelling of the equation of state with Sly5 parameters. Details of the NSE model can be found in ref. [5, 6]. The abundance of a cluster having Z protons and N $(A = Z + N)$ neutrons is connected to the internal Helmholtz free energy $F_{A,Z}$. For Hydrogen and Helium isotopes, no excited states are considered and the internal Helmholtz free energy is given by,

$$F_{A,Z} = E_{exp} + \Delta E(n_B, T, A, Z), \qquad (2)$$

where E_{exp} is the measured ground state energy, and ΔE is the binding energy shift that we want to extract from the comparison with the experimental chemical constants.

In order to do that, the baryonic density dependence of chemical constants (K_c^{free}) for ^{2}H, ^{3}H, ^{3}He, ^{4}He and ^{6}He are initially investigated from NSE model without in-medium correction and compared with the experimental data (see Fig. 1). It is clearly observed that at higher baryonic densities the theoretical values are overestimated which confirm the requirement of in-medium correction factor with the experimental biding energies.

*Electronic address: `swagato@vecc.gov.in`

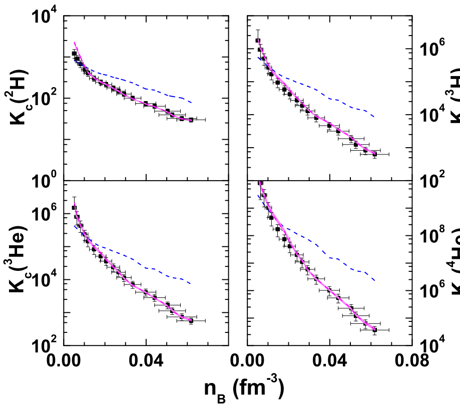

FIG. 1: Density dependence of theoretically calculated chemical constants without (blue dashed lines) and with (red solid lines) ΔE compared with experimental values (black squares).

Fig. 2 represents the density dependence of $X(A,Z) = \log_{10}\frac{K_c(A,Z)^{expt}}{K_c(A,Z)^{free}}$ for the light clusters which shows that $X(A,Z)$ is almost identical for ^{3}H and ^{3}He but different for various mass numbers, i.e. the in-medium binding energy shift strongly depends on A but the dependence on isospin asymmetry $N-Z$ is negligible. Therefore our next aim is to find the in-medium binding energy shift ΔE for a cluster of mass number A at each bary-

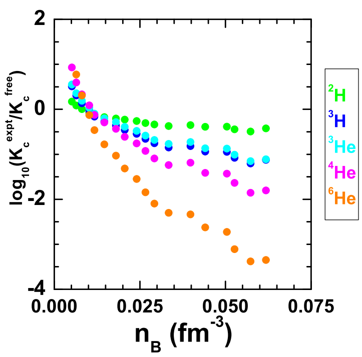

FIG. 2: Density dependence of the experimental deviation from the vacuum energy assumption $log_{10}\frac{K_c^{expt}}{K_c^{free}}$ for the different light clusters.

onic density which satisfies a simple power law $\Delta E = a + bA^c$, where a, b and c are fitting parameters. These parameters are calculated by the Bayesian approach and the density dependence of ΔE for light clusters are presented in Fig. 3. The density dependence of chemical constants with ΔE correction are determined in the framework of NSE model and also shown in Fig. 1.

In order to determine ΔE over a wide and

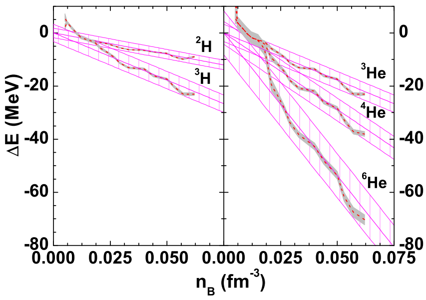

FIG. 3: Density dependence of ΔE extracted from the NSE model optimized on the experimental data. A linear fit of these curves is given by the magenta solid lines.

continuous density region we perform a linear fit $\Delta E = m.n_B$, results are also shown by the solid lines of Fig. 3 (shaded regions represent the standard deviation of the fit).

To conclude, we have determined the density and particle number dependent in-medium binding energy shift of the light clusters in a dense thermalized medium [6] which can be easily incorporated in future simulations in the astrophysical environment.

References

[1] A. Arcones, *et al.*, Phys. Rev. C **78**, 015806 (2008).
[2] L. Qin, *et al.*, Phys. Rev. Lett. **108**, 172701 (2012).
[3] H. Pais, *et al.*, Phys. Rev. Lett. **125**, 012701 (2020).
[4] R. Bougault, *et al.*, J. Phys. G **47**, 025103 (2020).
[5] S. Mallik and F. Gulminelli, Phys. Rev. C **103**, 015803 (2021).
[6] S. Mallik, H. Pais and F. Gulminelli, Eur. Phys. J. A **57**, 262 (2021).