Light particle clusterization in nuclear matter at very low density

L. Qin, J. B. Natowitz, G. Roepke,[1] K. Hagel, R. Wada, Z. Chen, P. Sahu, S. Kowalski,[2]
C. Bottosso, S. Shlomo, M. Barbui,[3] D. Fabris,[3] M. Lunardon,[3] S. Moretto,[3]
G. Nebbia,[3] S. Pesente,[3] V. Rizzi,[3] G. Viesti,[3] M. Cinausero,[4]
G. Prete,[4] T. Keutgen,[5] Y. El Masri,[5] and Z. Majka[6]
[1]*University of Rostock, FB Physik, Rostock, Germany*
[2]*Institute of Physics, Silesia University, Katowice, Poland*
[3]*Dipartamento di Fisica dell'Universita di Padova and INFN Sezione di Padova, Italy*
[4]*INFN Laboratori Nazionali di Legnaro, Italy*
[5]*Universit´e Catholique de Louvain, Louvain-la-Neuve, Belgium,*
[6]*Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*

Reliable understanding of the nuclear EOS over a range of densities remains a very important requirement in nuclear astrophysics. Several extensive calculations and existing tabulations, based on various models have been pursued, Recently, Horowitz and Schwenk have reported the development of a Virial Equation of State (VEOS) for low density nuclear matter [1]. At sufficiently low densities, this equation of state, derived from experimental observables should be "model-independent, and therefore set a benchmark for all low density nuclear equations of state. The importance of understanding low density nuclear matter in both nuclear physics and in the physics of the neutrinosphere in supernovae is emphasized in the VEOS paper [1] as well as in a recent paper by Sumiyoshi *et al.* [2].

At low densities and high temperatures strong alpha clustering of the matter is predicted. Such clusterization can be expected in low density nuclear matter, whether it be gas or the low density surface of an expanded high temperature nucleus. We recently adapted our investigations of the nucleon and light cluster emission that occurs in near Fermi energy heavy ion collisions to probe the properties of the low density participant matter produced in such collisions [3]. The reactions of 35 MeV/nucleon ^{64}Zn projectiles with ^{92}Mo and ^{197}Au target nuclei were studied. The data provide experimental evidence for a large degree of alpha clustering resulting from nucleon coalescence in this low density matter. For nuclear gases with average proton fraction, Yp ~0.44, and densities at and below 0.05 times normal nuclear density and varying temperatures experimental symmetry energy coefficients have been derived using the isoscaling method.

The resultant symmetry energy coefficients are plotted against density in Fig. 1 where they are compared to those which are predicted by the Gogny effective interaction and to the 31.6 x $(\rho/\rho_0)^{1.05}$ dependence suggested by a recent analysis of isospin diffusion data [4]. These symmetry energies reported in Fig. 1 are far above those obtained in common effective interaction calculations and reflect cluster formation, primarily of alpha particles, not included in such calculations. Stimulated by these data, Schwenk and his collaborators have since improved the VEOS model with the addition of ^{3}H and ^{3}He cluster coefficients [5].

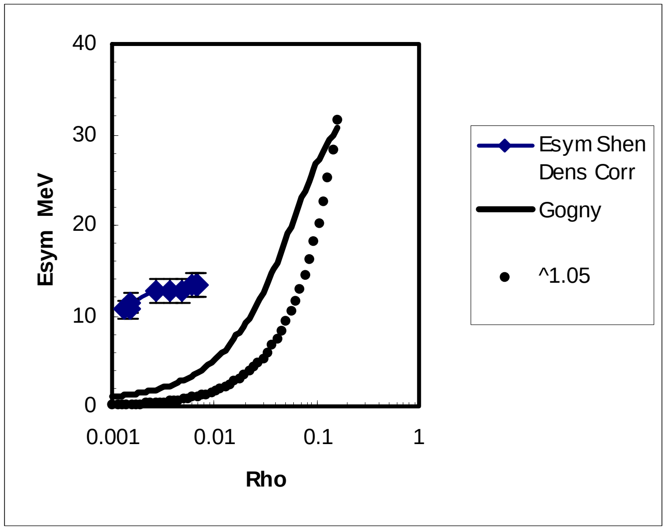

Figure 1. Derived symmetry energy coefficients as a function of baryon density. Solid diamonds indicate experimental results. Solid line indicates the variation predicted by the Gogny interaction. The dotted line represents the function 31.6 x $(\rho/\rho_0)^{1.05}$.

Our original analysis has assumed that at such low density the chemical equilibrium model of Albergo *et al.* should be applicable. Extracting information at higher densities is clearly desirable but requires a more sophisticated analysis. This is made clear from a number of theoretical results [6-8]. For example, in Fig. 2 we present results of Roepke *et al.* who have calculated the in-medium binding energies of clusters as a function of temperature and density. As seen in Fig. 2 for a temperature of 10

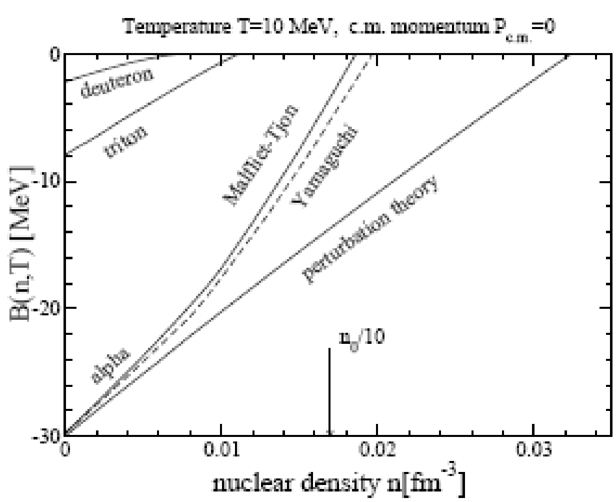

Figure 2. In medium binding energies of light clusters

MeV, the free binding energies of the clusters (at 0 on the density axis) decrease with increasing density and reach 0 at a point known as the Mott density. Using this model, G. Roepke has made calculations of the low density symmetry energy for comparison to our experimental results [8].

In order to pursue this effort of taking the in medium modifications into account and broaden the density range over which the symmetry energies are experimentally determined we have now carried out a series of experiments in which the reactions of ^{112}Sn and ^{124}Sn with a wide range of projectiles, ranging from p to ^{64}Zn, all at the same energy per nucleon, 47Mev/u, could be studied. The systems chosen for this study, the PhD thesis of LiJun Qin, were : ^{4}He, ^{10}B, ^{20}Ne, ^{40}Ar and ^{64}Zn projectiles with ^{112}Sn and ^{124}Sn targets. In this series of experiments different collision systems should lead to different average densities, the analysis is nearing completion. As an example of our results, Fig. 3 presents preliminary results in which our experimental results for alpha mass fractions in low density nuclear matter with T = 5 MeV are compared to the results of various calculations as indicated in the label box.

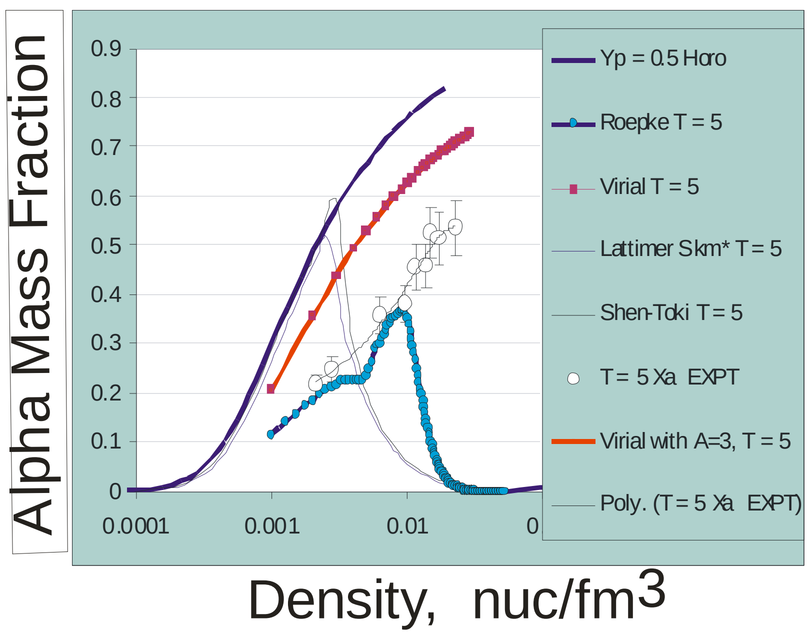

Figure 3. Alpha mass fraction in low density matter. See text.

[1] C. J. Horowitz and A. Schwenk, Nucl. Phys. A **776**, 55 (2006).

[2] K. Sumiyoshi and G Roepke , arXiv:0801.0110

[3] S. Kowalski *et al.*, Phys.Rev. C **75**, 014601 (2007).

[4] L. -W. Chen *et al.*, Int. J. Mod. Phys. **E15**, 1385 (2006).

[5] E. O'Connor *et al.*, Phys. Rev. C (to be published); arXiv:nucl-th/0702044.

[6] M. Beyer *et al.*, Phys.Lett. **B488**, 247 (2000).

[7] M. Beyer *et al.*, Eur.Phys .J. **A22**, 261 (2004).

[8] G. Roepke (private communication).