In-Medium phenomena in Low Density Nuclear Matter

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Abstract. In-medium phenomena of low density nuclear matter are studied using collisions of 47 A MeV $^{40}$Ar and $^{64}$Zn projectiles with $^{112}$Sn and $^{124}$Sn target nuclei. Low density equations of state are tested by confronting various models with the data. In-medium cluster binding energies and symmetry density are also studied at low densities. We find that models that account for in-medium effects in general describe the data better than models that do not.
I. Introduction
Understanding the properties of low density nuclear matter and how the properties evolve with changes in density have become very important subjects in recent times. Any investigation into nuclear and astrophysical phenomena, for example, requires an understanding of the symmetry energy of nuclear matter. Our understanding of stellar evolution and supernovae requires an understanding of the nuclear equation of state over a wide range of temperatures and densities. In addition, the assumption that properties of species in equilibrium are the same as those of the isolated species is tenable only at densities approaching zero density (i.e. very low densities). In-medium effects lead to a dissolution of clusters as the density increases.

Our group has performed a series of measurements studying various properties of nuclear matter at low densities [1, 2, 3, 4, 5]. In this paper we provide a summary of recent work [3, 4, 5] that we have performed on the subject of low density nuclear matter.

II. Experimental Method and Observables
The NIMROD 4π multi-detector at Texas A&M University was used for the measurements presented here. Collisions of 47A MeV ⁴⁰Ar with ¹¹²,¹²⁴Sn and ⁶⁴Zn with ¹¹²,¹²⁴Sn were analyzed. NIMROD consists of a 166 segment charged particle array set inside a neutron ball [6]. The details of the experimental setup may be found in [1, 2, 3, 4, 5].

We focus on the reaction products from the intermediate velocity (IV) source for the analysis presented in this work. The IV source is treated as a fireball created early in the participant interaction zone. In the following we use the energy spectra measured in NIMROD detectors centered at approximately 40°. This ring was chosen because it is near 90° in the center of mass in 47A MeV ⁴⁰Ar with ¹¹²,¹²⁴Sn and ⁶⁴Zn with ¹¹²,¹²⁴Sn collisions. The spectra at these angles minimize the contributions from the projectile and target sources thereby enhancing the contribution from the IV source.

In order to study density dependencies we have employed the coalescence model [7, 8, 9]. Various applications of the coalescence model [10, 11] allow extraction of information on the density dependence of nuclear matter[3, 4, 5]. The Awes model [11] includes Coulomb corrections with a formulation to extract $P_0$, the interaction radius in momentum space, from laboratory energy spectra. The Mekjian model [10] uses the assumption of thermal and chemical equilibrium model to determine the coalescence yield of all species which leads to a direct relation between $P_0$ and the emitting system volume.

Figure 1 shows $P_0$ parameters extracted from the Awes model [11] as a function of surface velocity, $v_{surf}$, the velocity of the particle after subtraction of the Coulomb energy. $v_{surf}$, on average, is related to the time of emission from the hot region [12]. The evolution of $P_0$ with $v_{surf}$ results from the expansion and cooling of the participant interaction zone. This is seen when using the volume to extract the dependence of density on $v_{surf}$. In figure 2 we employ the Mekjian model to extract the volume. The volume as a strong dependence on $v_{surf}$ which shows the time evolution of the size of the system. We note that the information on the volume obtained from $t$. ³He and ⁴He give similar values whereas the information using $d$ results in higher values. We take this to be an effect of the binding energy of the deuteron in that it is easier to break up and therefore has a smaller yield leading to larger volume parameters. We therefore use information from particles with $A \geq 3$ to calculate densities.

Temperatures can be extracted as a function of $v_{surf}$ [1, 2] using the Albergo model [13]. We used the Albergo model on our measured energy spectra to extract these temperatures and figure 3 shows the resultant temperature density relation. We note that higher temperatures are associated with higher densities. This correlation shows the evolution of density and temperature that results from the nascent fireball created in the participant interaction zone and is consistent with a picture of a system that is initially hot and at relatively high density and then cools as it expands.
III. Results and Discussion

Low density tests of the nuclear equation of state

Information on the nuclear equation of state over a wide range of temperatures and densities is important to understanding stellar evolution and supernovae. Many calculations have been performed and there is a wide disparity in quantitative predictions. Much of this disparity probably reflects differences in the treatment of possible competing species. Therefore if relevant species are not included in the calculation, the calculated mass fractions of the included species
In order to have results independent of the choice of competing species we therefore compare equilibrium constants derived from the experimental data with those derived from the models. The equilibrium constants are defined as

$$K_{c}(A, Z) = \frac{\rho(A, Z)}{\rho_p^Z \rho_n^{(A-Z)}}$$

where $\rho(A, Z)$, $\rho_p$ and $\rho_n$ are the densities of cluster of mass $A$ and atomic number $Z$, free protons and free neutrons, respectively. The densities are expressed in units of nucleons/fm$^3$. Figure 4 shows equilibrium constants derived the $d$, $t$, $^3$He and $^4$He in the experimental data. Recall from figure 3 that temperature increases with increasing density.

In figure 5 we focus on the $^4$He equilibrium constants. In this figure we compare the experimentally extracted constants to the equilibrium constants predicted by a number of available EOS calculations at low density. The red diamonds connected by dashed red line show the experimental data. We note that the predictions of the different models vary by several orders of magnitude over the entire range of density shown. The figure also shows that the trends of the different models vary in addition to the differences in absolute value.

Among the model predictions that show the best agreement with the data for all except the lowest densities are the Lattimer and Swesty calculations that employ Skyrme interactions with incompressibilities of 180 and 220 MeV [14]. The data suggest that a value of 220 is more...
Figure 5. Comparison of experimental values of $K_c(\alpha)$ with those from various EOS calculations. The shaded band indicates the uncertainty in density for the experimental data.

appropriate as the predictions using a value of 180 fall off at the higher densities much more than the data. The QSM model \cite{15, 16} results with the latest estimates of momentum dependent in-medium binding energy shifts also reproduce the data quite nicely. An NSE model which includes excluded volume effects is in good agreement with the data at the higher densities.

**In-medium cluster binding energies**

Using the definition of equilibrium constants from equation 1 and the Albergo model, it can be shown that \cite{5}

$$K_c(A, Z) = C(T) \exp \frac{B(A, Z)}{T}$$

(2)
where $C(T)$ is a constant that absorbs the spin factors, internal partition function, thermal wavelength and densities found in the Albergo formulation [13]. Since the Albergo formulation does not explicitly include entropy contributions we include a mixing entropy term [17]. This leads to the following expression for the binding energy:

$$\frac{B}{T} = \ln[Ke/C(T)] + Z\ln(Z/A) + N\ln(N/A)$$  \hspace{1cm} (3)

We can therefore determine the apparent binding energies, $B(\rho, T)$, using the experimentally determined equilibrium constants and temperatures. Figure 6 shows the density dependence of $B(\rho, T)$ for $d$, $t$, $^3$He and $^4$He clusters. The binding energies of all species decrease monotonically with increasing density.

A Mott point is, by definition, the combination of density and temperature where the binding energy is zero with respect to the surrounding medium. Figure 7 shows the Mott points extracted from figure 6 for each cluster at the temperature and density that was sampled in the experiment. Also shown in figure 7 are polynomial fits to Mott points presented in reference [15] using a thermodynamic Green function method that makes explicit use of an effective nucleon-nucleon interaction to account for in-medium effects on cluster properties [18]. We note that the model predicts the experimental data quite well.

**Low Density Symmetry Energy**

Figure 8 shows the Free symmetry energy coefficients extracted from our isoscaling analysis [3]. The figure also shows calculations for several temperatures of the Free symmetry energy coefficients extracted from a quantum statistical approach that includes medium modifications of the cluster binding energies [15, 16, 19, 20, 21]. The general behavior of the experimental data is reproduced by the calculations fairly well.
The symmetry entropy must be known in order to derive the internal symmetry energy and this contribution must be calculated. Figure 9 shows for the same temperatures the calculated symmetry entropy, the difference between the entropy of neutron matter and that of symmetric matter, using quantum statistical calculations of momentum dependent energy shifts of light clusters [16].

The symmetry energy values as derived using figures 8 and 9 are shown in figure 10. Also shown are the predictions of the model calculated for the different temperatures. We note that the model predicts values in the range of the experimental data, but the trend is not obviously the same. Recall again that T changes as the density changes.

IV. Summary and Conclusions

We have studied a series of low density nuclear phenomena. Different available models have been confronted with the data using various experimental observables. Using equilibrium constants to confront various astrophysical EOS calculations at low density with the data suggests an incompressibility between 180 and 220. Models that treat in-medium effects in general do a better job of fitting the data.

We also presented an experimental determination of in medium cluster binding energies and Mott points for \( d, t, ^3\text{He} \) and \( \alpha \) clusters produced in low density nuclear matter. Our results are in good agreement with those predicted by a recent model which explicitly treats these quantities.

Finally we have derived the symmetry energy from the data and once again confronted the models with the data. Again, calculations that account for in-medium effects describe the data.

It is clear from this series of studies that accounting for in-medium effects is important in the study of low density nuclear matter.

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