Equation of State Effects on Nucleon Transport

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Abstract. Previous studies have examined the nucleon transport in charge symmetric beam-on-target reaction systems as a probe for the asymmetry energy of nuclear matter. Using the iBUU transport model, isospin transport in charge symmetric as well as mass symmetric systems of Zn and Ni isotopes at 35 MeV/nucleon will be explored. Comparisons of the behavior of charge symmetric (70,64Zn + 70,64Zn) to mass symmetric (64Zn,64Ni + 64Zn,64Ni) reaction systems will be studied. The effect of different nucleon interactions will also be studied. This set of reaction systems will be used to determine what effect the difference in charge between projectile and target may have on the proton transport as compared to the neutron transport. These studies will be carried out with a view for use in the analysis of experimental data acquired using the NIMROD-ISiS array and TAMU Neutron Ball at the Cyclotron Institute at Texas A&M.

1. Introduction
The nuclear equation-of-state (nEoS) has been well studied for symmetric nuclear matter at nuclear saturation densities. However, there are not strong constraints on the density dependence of the asymmetry energy at sub-saturation densities [1]. Better understanding of this behavior can help extrapolate to other systems, like neutron stars. Nucleon transport, which includes isospin drift and isospin diffusion, describes the interaction and movement of nucleons between projectile and target in a nuclear reaction. Isospin diffusion, the transport of nucleons due to differences in isospin content, can be used to further constrain the density dependence of the asymmetry energy [2,3].

Transport calculations (like the isospin-dependent Boltzmann-Uehling-Uhlenbeck, or iBUU model) utilize test particles and a mean-field potential to simulate the interaction of particles during a nuclear reaction. By examining the behavior of these test particles under different impact parameters for various inputs, information about the transport of nucleons can be determined.

2. Experiment
Reactions for 35 MeV/u 70,64Zn,64Ni+70,64Zn,64Ni, as seen in table 1, were modeled using iBUU04 [4]. Table 1 also gives the corresponding projectile, target and composite system (CS) neutron to proton ratios (N/Z). The reactions were allowed to run out to 100 fm/c, where it was determined that the quasi-projectile (QP) and quasi-target (QT) were well separated while only a modest number of test particles had been lost.
outside of the bounding box of the model. The reactions were simulated at discrete impact parameters from 0-10 fm. The simulations were carried out using 193 test particles per nucleon.

Table 1. Projectile, target and composite system neutron to proton ratios for reaction systems simulated at 35 MeV/u using the iBUU04 transport code.

| System                  | Projectile N/Z | Target N/Z | Composite System N/Z |
|-------------------------|----------------|------------|-----------------------|
| \(^{70}\text{Zn} + ^{70}\text{Zn}\) | 1.333          | 1.333      | 1.333                 |
| \(^{70}\text{Zn} + ^{64}\text{Zn}\) | 1.333          | 1.133      | 1.233                 |
| \(^{64}\text{Zn} + ^{64}\text{Zn}\) | 1.133          | 1.133      | 1.133                 |
| \(^{64}\text{Zn} + ^{64}\text{Ni}\) | 1.133          | 1.286      | 1.207                 |
| \(^{64}\text{Ni} + ^{64}\text{Ni}\) | 1.286          | 1.286      | 1.286                 |

One hundred primary events were simulated for both “stiff” \((x= -2)\) and “soft” \((x= 1)\) parameterizations of the nEoS. Figure 1 shows the asymmetry energy \((E_{\text{sym}})\) as a function of reduced density (nuclear density over nuclear saturation density, \(\rho/\rho_0\)) for several parameterizations of the interaction in iBUU04. The curves shown are the density dependent symmetry energies that correspond to various input parameters \((x= -2 \text{ to } 1)\) for the momentum dependent interaction in iBUU04 [5].

![Figure 1. Nuclear Asymmetry Energy as a function of nuclear density in iBUU04 for several different parameterizations of the nEoS [5].](image)

3. Quasi-projectile definition
To analyze the transport during interaction of projectile and target, the QP (hot projectile-like remnant) needs to be identified and studied. In order to do this, the reaction-plane density plots of the simulation are examined at 100 fm/c, the simulation stop time. A geometry cut is defined by taking a line that connects the two highest density points (i.e. the centers of the QP and QT) and a perpendicular bisector of this density-connect line is calculated as seen in figure 2. All test particles on the target side is tentatively identified with the QT, while test particles on the projectile side are identified with the QP. A spherical density cut is then applied to the centers of both the QP and QT. This is done by generating a set of vectors defining a spherical shell that are matched in magnitude to the low density region away from the QP (QT) corresponding to \(~1/10\text{th}\) \(\rho_0\). These vector magnitudes are then averaged, and a sphere of this radius is
generated surrounding the high-density center of the QP. All test particles located inside the spherical shell are identified as part of the QP (QT) and can be seen by the red circle in the bottom of figure 2.

Figure 2. Density profile of $^{70}$Zn+$^{70}$Zn at $b=6$ fm. Red lines indicate various lines and parameters for making quasi-projectile cuts. The green box shows expanded geometry cut region around the QP.

4. Analysis of Quasi-projectile isospin content

Figure 3. Fraction of test particles originating from the projectile as a function of impact.

Figure 4. Fraction of test particles originating from the projectile as a function of impact.
At small impact parameters (more violent collisions), we expect an increase in the exchange of matter between projectile and target. Figure 3 shows this trend as well as the relative insensitivity to the system. We see here that the fraction of test particles in the QP (QT) that originated from the initial projectile decreases (increases) with the violence of the collision. However, within the 5 reaction systems studied ($^{70}$Zn+$^{70}$Zn - black circles, $^{70}$Zn+$^{64}$Zn – red squares, $^{64}$Zn+$^{64}$Zn – green inverted triangles, $^{64}$Zn+$^{64}$Ni – blue triangles, $^{64}$Ni+$^{64}$Ni – light blue stars), there is very little difference between systems, suggesting the gross movement of nucleons during transport is isospin independent. In figure 4 we see the same measure for the $^{70}$Zn+$^{70}$Zn reaction for two different nEoS. Again, there appears to be no change in the gross transport with respect to isospin.

While the bulk exchange of nuclear matter sees little effect with isospin, the question remains what effect isospin differences have on proton and neutron transport individually, rather than taken collectively. This can be determined by examining the evolution of the neutron to proton ratio (N/Z) as a function of impact parameter. Figures 5 and 6 both show QP (solid symbols) and QT (open symbols) N/Z as a function of impact parameter. The systems depicted are: $^{70}$Zn+$^{70}$Zn (black circles, top panels), $^{70}$Zn+$^{64}$Zn (red squares, middle panels) and $^{64}$Zn+$^{64}$Ni (blue triangles, bottom panels). The solid color lines show the composite system of projectile-projectile, target-target and projectile-target for each system. Figure 5 is data simulated from the “stiff” nEoS while figure 6 refers to the “soft” nEoS.

Parameter for both the QP and QT for all 5 reaction systems (see text).

Parameter for $^{70}$Zn+$^{70}$Zn for two different nEoS ($x=1$ and $x=-2$).

Figure 5. Neutron to proton ratio (N/Z) as a... Figure 6. Neutron to proton ratio (N/Z) as a...
function of impact parameter for QPs and QTs of various reaction systems. Simulated using “stiff” nEoS. Solid lines in each panel give the N/Z values of initial projectiles and targets as well as composite system N/Z.

function of impact parameter for QPs and QTs of various reaction systems. Simulated using “soft” nEoS. Solid lines in each panel give the N/Z values of initial projectiles and targets as well as composite system N/Z.

For the symmetric reaction of $^{70}\text{Zn}+^{70}\text{Zn}$ in the top panel of figure 5, the N/Z content of both QP and QT mostly matches that of the composite system (solid black line). There is a slight dip in the N/Z at mid-peripheral impact parameters (b=6-9) which could indicate loss of neutron-rich content to the predicted high N/Z “neck” formation. An increase in N/Z appears to occur as we approach very central impact parameters (b=0-4) which could suggest that loss of nuclear matter to the surrounding “gas” may be rich in N=Z isospin symmetric content. However, it is important to note that the shaded region (central impact parameters of b=0-4 fm) indicates a region where true QP formation cannot be assured due to the violence of the collision.

For the asymmetric reactions ($^{70}\text{Zn}+^{64}\text{Zn}$ in the middle panel and $^{64}\text{Zn}+^{64}\text{Ni}$ in the bottom panel), the QP and QT N/Z values begin near the initial projectile and target N/Z contents, respectively. Decreased impact parameter (small b) implies longer contact time between projectile and target, which could allow more N/Z mixing to occur, driving toward N/Z equilibration. While the QP and QT N/Z do NOT approach composite system N/Z, the similarity between the QP and QT N/Z at small impact parameters suggests N/Z equilibration. Deviation of the N/Z value from that of the composite system could be a result of the evolving state of the system as nucleons migrate to the neck region, as well as the surrounding gas.

The “soft” nEoS in figure 6 gives very similar results. The N/Z content for the symmetric system (top panel) mirrors that of the composite system (black line) with a slight drop in the N/Z. There is very little variation with impact parameter, suggesting the “soft” nEoS may exhibit a different set of dynamic processes from that of the “stiff” nEoS. The asymmetric reactions (middle and bottom panels) for the “soft” case are similar to the “stiff” in that the QP and QT N/Z begin near initial projectile and target N/Z contents and converge toward each other at small impact parameters. Interestingly, the “soft” nEoS shows this convergence to occur around the value of the composite system N/Z, unlike in the “stiff” case. The differences in the QP and QT composition as a function of the violence of collision seen in Figures 5 & 6 have some interesting features. While at the moment we have no answer for the differences seen in the equilibration between soft and stiff symmetry energies, this is an interesting phenomenon which warrants further study.

5. Conclusion
If we define N/Z equilibration as the point where the N/Z content of the QP and QT are the same, then we can see the “soft” asymmetry energy reaches N/Z equilibrium at a much larger impact parameter than in the “stiff” case. This is similar to the effect seen by Tsang et al. [2] and Baran et al. [6] when looking at equilibration as a function of the time evolution of the system. The form of the asymmetry energy does, however, change the N/Z value at which this equilibration occurs. The form of the asymmetry energy also has a large impact on the composition of the QP, determining the differential exchange of protons and neutrons, if not the overall exchange of nucleons. Baran et al. has also predicted isospin dependence of “neck” formation/breakup and emission to the “gas” that is consistent with this work. Further study could include possible experimental examination of the “neck” and “gas” emission as well as experimental confirmation of N/Z content trends with impact parameter. In order to accomplish this, it is clear that impact parameter determination will be critical in experimental data.
References

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