Equation of state effects on Nucleon Transport

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The nuclear equation-of-state (EoS) has been well studied for symmetric nuclear matter at nuclear saturation densities. However, there are not strong constraints on the density dependence of the symmetry energy at sub-saturation densities. Nucleon transport, which includes isospin drift and 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 symmetry energy [1,2].

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 [3,4]. By examining the behavior of these test particles under different impact parameters for various inputs, information about the transport of nucleons can be determined. Reactions for 35 MeV/u $^{70,64}Zn, ^{64}Ni + ^{70,64}Zn, ^{64}Ni$ as seen in Table 1 were modeled using iBUU04. 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.

Table I. These reactions were simulated over a range of impact parameters at 35 MeV/u using the iBUU04 transport code. Listed are the N/Z content of the initial system projectile, target and composite system.

System	Projectile N/Z	Target N/Z	Composite System N/Z
$^{70}Zn + ^{70}Zn$	1.333	1.333	1.333
$^{70}Zn + ^{64}Zn$	1.333	1.133	1.233
$^{64}Zn + ^{64}Zn$	1.133	1.133	1.133
$^{64}Zn + ^{64}Ni$	1.133	1.286	1.207
$^{64}Ni + ^{64}Ni$	1.286	1.286	1.286

The QP (and QT) is defined from the test particle output via an algorithm which cuts particles which do not match certain criteria. First, a geometry cut is defined by a line that connects the two highest test particle density centers (i.e. the centers of the QP and QT) located in the simulation. A perpendicular bisector of this line is calculated. Everything 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 center of the QP (and QT) to better define a "source." A set of vectors defining a spherical shell are matched in magnitude to the low density region radially away from the QP (QT) corresponding to $\rho_0/10$. These distances are then averaged, and a sphere of this radius is generated around the high-density center. All test particles inside the sphere are chosen as part of the QP (QT respectively).

The simulation is run over a large range in impact parameter, from 0fm (central collisions) out to 10fm (approximately touching-spheres for all systems). Small impact parameters (more violent collisions) correspond to increased exchange of matter. The QP exchanges matter with the target as you move to more central collisions while the QT exhibits similar behavior, exchanging matter with the projectile. Similar behavior for QP and QT of gain and loss of particles is largely independent of system and parameterization of EoS.

As seen in the top left panel of Fig. 1, the N/Z content mostly matches that of the composite system (black line) for the symmetric ^{70}Zn+^{70}Zn system for a "stiff" interaction (x=-2 parameter in iBUU). A slight dip in N/Z at mid-peripheral impact parameters could indicate loss of high N/Z content to the predicted high N/Z "neck" formation in collisions at these energies. Additionally, high N/Z at very central impact parameters could suggest that loss of nuclear matter to the surrounding "gas" may be rich in N=Z content.

In the middle left and lower left panels we see that for the asymmetric reactions, QP and QT N/Z begin near the value of 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. While QP and QT N/Z do not approach composite system N/Z, the similarity between 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 the result of nucleons migrating to the neck region and evaporating to the surrounding gas.

The top right panel of Fig. 1 (which is the same as the top left panel, but for "soft" interaction, iBUU MDI parameter x=1) shows that the N/Z content mirrors that of the composite system (black line) with a slight drop in N/Z. There is very little variation with impact parameter in the "soft" case. The middle right and lower right panels show the "soft" case for the asymmetric systems. Similar to the "stiff" case, the "soft" QP and QT N/Z begin near initial projectile and target N/Z values, respectively, while the QP and QT N/Z converge at small impact parameters to the values of the composite systems. The "soft" symmetry energy reaches N/Z equilibrium (convergence between QP and QT) at a much larger impact parameter than in the "stiff" case. This is similar to the effect seen by Tsang *et. al* . and Baran *et. al.* when looking at equilibration as a function of time[5,6]. We can see from comparing the left and right sides of Fig. 1 that the form of the symmetry energy has a large impact on the QP and its composition. Baran *et. al.* has also predicted the isospin dependence of neck formation/breakup and emission to the gas that is consistent with this work. It may be possible to examine the "neck" and "gas" emission experimentally, this will be investigated further. It is clear that impact parameter determination will also be critical for event characterization and analysis of these effects in the experimental data. Work will continue on the simulations to find a surrogate for the impact parameter, since impact parameter cannot be directly measured experimentally.
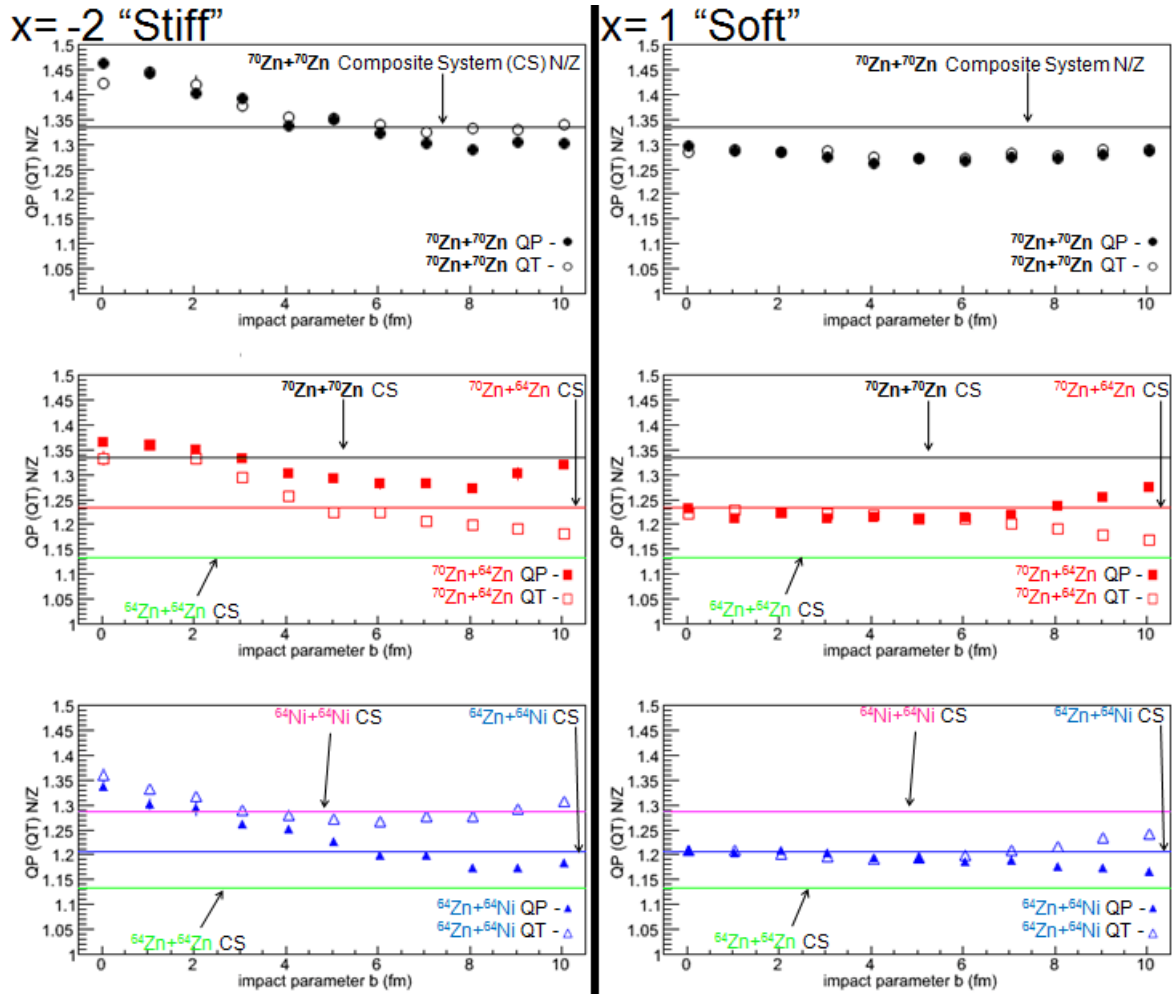
FIG. 1. The N/Z content of QP and QT by impact parameter for various systems and EoS. **Top panels:** For the symmetric ^{70}Zn+^{70}Zn reaction, the N/Z content of the QP (solid) and QT (open) are shown with the composite system (black line). **Middle panels:** For the mass asymmetric ^{70}Zn+^{64}Zn reaction, QP (solid red square) and QT (open red square) N/Z are shown with projectile (black line), target (green line) and composite system (red line) N/Z. **Lower panels:** For the charge asymmetric ^{64}Zn+^{64}Ni reaction, QP (solid blue triangle) and QT (open blue triangle) N/Z are shown with projectile (green line), target (pink line) and composite system (blue line) N/Z.

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