t/^{3}He as a Probe to Study Neutron Enrichment

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An increasing amount of experimental data is available now on various aspects of heavy ion reactions at low and intermediate energies. Depending on the system, incident energy and impact parameter, one observes different phenomena ranging from fusion, incomplete fusion, binary deep inelastic reactions, deep inelastic collisions and multifragmentation. Much theoretical work has been done in order to describe the observed phenomena.

Theoretically, it is predicted that a higher density (liquid) phase of a system has about the same number of protons and neutrons, and so the excess neutrons are accumulated at a lower density (gaseous) phase. Also, it is expected that the neck region is a gaseous transition and therefore has a higher N/Z compared to the total system.

In this project we examined the neutron enrichment between the proton-rich ^{112}Sn + ^{112}Sn and the neutron rich ^{124}Sn + ^{124}Sn systems. It would be ideal if the n/p ratio could be measured for these systems, but neutrons are very difficult to detect in an experiment. Intuitively, however, one expects that the n/p ratio is proportional to the t/^{3}He ratio. Therefore, instead of trying to detect the emission of neutrons, the productions of t and ^{3}He were used as observables for ^{112}Sn + ^{112}Sn and ^{124}Sn + ^{124}Sn reactions at E/A = 50 MeV. A comparative study of the experimental observations with predictions of microscopic Boltzmann-Uehling-Uhlenbeck (BUU) transport calculations has been performed.

The experiment was performed at the National Superconducting Cyclotron Laboratory (NSCL). LASSA (Large Area Silicon Strip Array) was used to measure and identify charged particles with Z ≤ 20, and it indicated the probability of detecting particles by finding their various positions and energies. The array consists of nine telescopes, and each of the telescopes contains sixteen single sided silicon strips, thirty-two double sided silicon strips and four CsI crystals. One of the charge particle detectors is shown in Figure 1. The Silicon strips were used to determine both the scattering angles of the incoming particles through position measurements and energy loss, while the purpose of the CsI crystals was to measure the energies only.
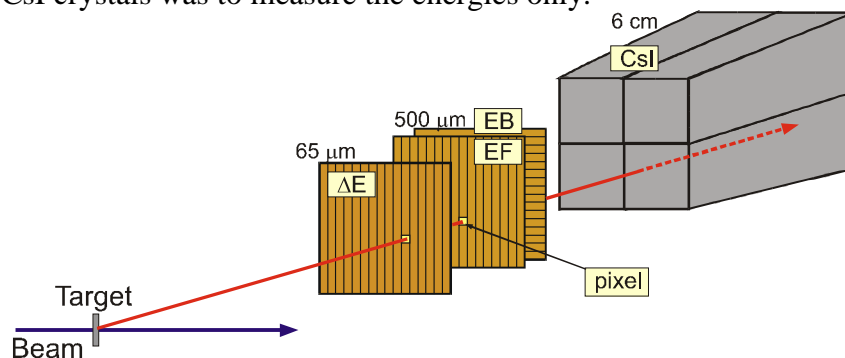

Figure 1. Schematic of one detector in LASSA

Figure 2 shows the observed energy detected by the Silicon detectors vs. the energy detected by CsI detectors for the ^{124}Sn + ^{124}Sn reaction at E/A = 50 MeV. Since Energy$_{Si}$ * Energy$_{CsI}$ $\propto$ AZ^2, where A is the mass of a particular nucleus and Z is the charge, the particles can be identified by the PID (Particle Identification) lines shown in Figure 2. Each line corresponds to one isotope value with particular A and Z. In Figure 2, the PID lines from the lower-left to the upper right represent p, d, t, ^{3}He, α-particle and Li respectively. A precise calibration was done for further data analysis. The following analysis focuses on particles emitted from the reaction zone, and it is restricted to particles emitted at large center-of-mass angles, 90° ± 30°.
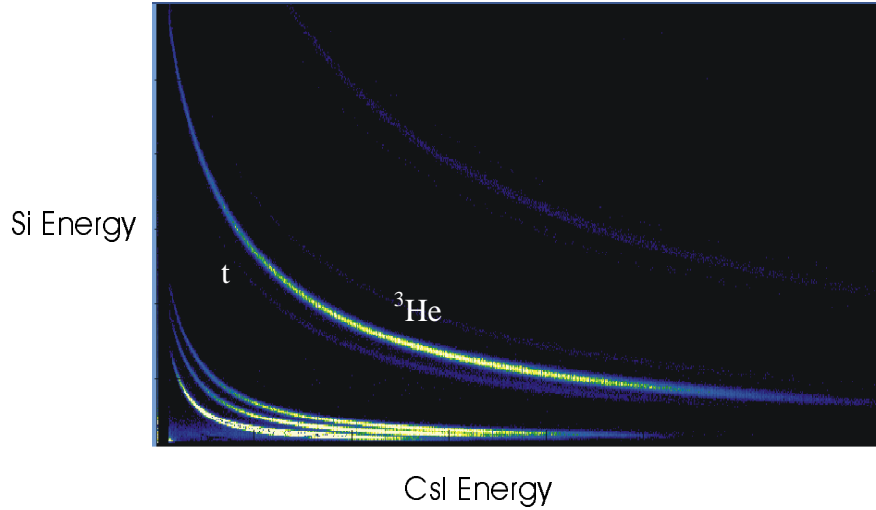

Figure 2. Energy of Si detectors vs. Energy of CsI detectors for ^{124}Sn + ^{124}Sn at E/A = 50 MeV

The BUU model is a transport model using Monte Carlo technique to simulate the equation of motion of nucleons in collision. This model has been improved in the past and it incorporates the dynamics formation of light clusters with A ≤ 3 (p, n, d, t, ^{3}He). Note that α-particles are not considered due to technical difficulty. The reaction simulations were being tested by examining reactions of ^{112}Sn + ^{112}Sn and ^{124}Sn + ^{124}Sn at E/A = 50 MeV, with no isospin potential. In order to simulate the mean field, 170 test particles representing each nucleon was used. The data was examined in a number of different manners. Specifically, the model was investigated to check whether it would reproduce the large magnitude of the t/^{3}He ratio observed experimentally, the dependence on the isospin of the initial systems, and the sensitivity of the dynamics of intermediate-energy heavy-ion collisions to the nuclear equation of state (EOS) of nuclear matter. Additionally, correlation between the t/^{3}He ratio and the n/p ratio was studied.

Figures 3a and 3b show the simulations which obtained from the BUU predictions for a collision of ^{124}Sn + ^{124}Sn with impact parameter b = 3 fm and 7 fm at 50 MeV respectively. The former simulation used Soft EOS while the latter one used stiff EOS. These figures show the projections of the total density. It indicates there are at least two different phenomena – ring system and neck system. Simulations for other impact parameters (0 fm, 1 fm, 5 fm and 9 fm) produce similar graphs as in Figure 3. But for a

head-on collision, the system tends to produce a ring, while systems with medium impact parameters tend to form necks, and the target and projectile-like nuclei systems with large impact parameters have elastic collisions.
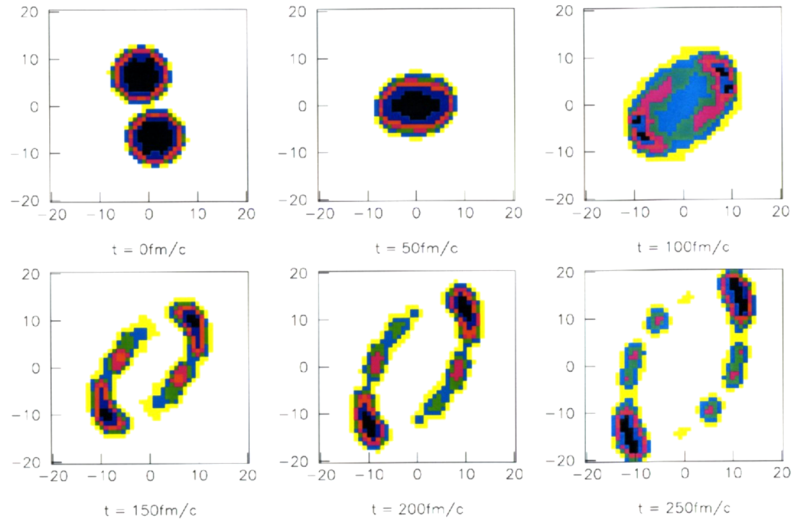

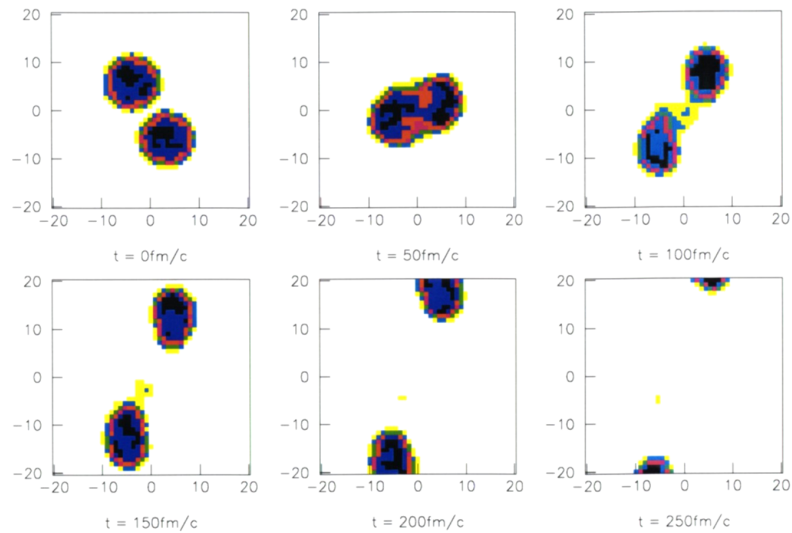**Figure 3a. Simulation of the BUU model for ^{124}Sn + ^{124}Sn with b = 3 fm at 50 MeV**

Figure 3b. Simulation of the BUU model for ^{124}Sn + ^{124}Sn with b = 7 fm at 50 MeV

Figure 4 shows the relationship between t/^{3}He and n/p ratios from the BUU model for the reactions of ^{112}Sn + ^{112}Sn and ^{124}Sn + ^{124}Sn at E/A = 50 MeV. This simulation was performed using the stiff EOS without isospin dependence to verify the t/^{3}He and n/p ratios relationship. A gate of 90° ± 30° was applied to the systems at the center-of-mass. The light dotted line indicates the points where t/^{3}He ≡ n/p. The BUU model suggests a strong linear correlation between t/^{3}He and n/p ratio.
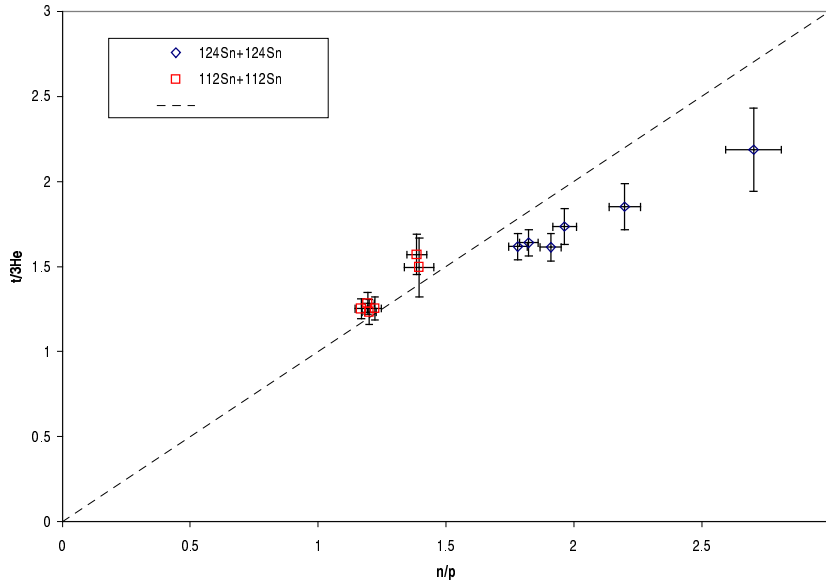
Figure 4. Predictions of the BUU model.

Figure 5 presents the observed yield ratio $t/^3He$ as a function of b_hat for experimental data and theoretical predictions resulted from solving the BUU model, where b_hat = b/b_{max}. Experimental data are shown by red solid square and blue diamond points for the $^{112}Sn + ^{112}Sn$ and $^{124}Sn + ^{124}Sn$ collisions respectively, while the open red square and blue diamond points present the results of the BUU model for the $^{112}Sn + ^{112}Sn$ and $^{124}Sn + ^{124}Sn$ simulations respectively. The light dot lines indicate the initial neutron-to-proton ratio of N/Z = 1.24 for the $^{112}Sn + ^{112}Sn$ reaction and N/Z = 1.48 for the $^{124}Sn + ^{124}Sn$ reaction. The figure shows that the theoretical $t/^3He$ ratios for the $^{112}Sn + ^{112}Sn$ and $^{124}Sn + ^{124}Sn$ reactions are very similar to their initial neutron-to-proton content of projectile and target, N/Z = 1.24 and 1.48 for the two simulations respectively.

However, calculations at intermediate energy do not agree with the observed $t/^3He$ yield ratio. At all impact parameters, the model significantly under predicts the experimental $t/^3He$ yield ratio. For central collisions, the observed experimental $t/^3He$ ratio is more 3 times than the predicted model. These calculations predict a too small $t/^3He$ yield ratio at mid-rapidity, where the cluster rapidity approaches the center-of-mass value. The present calculations do not reproduce the large experimentally observed excess of t emission compared to ^3He emission.
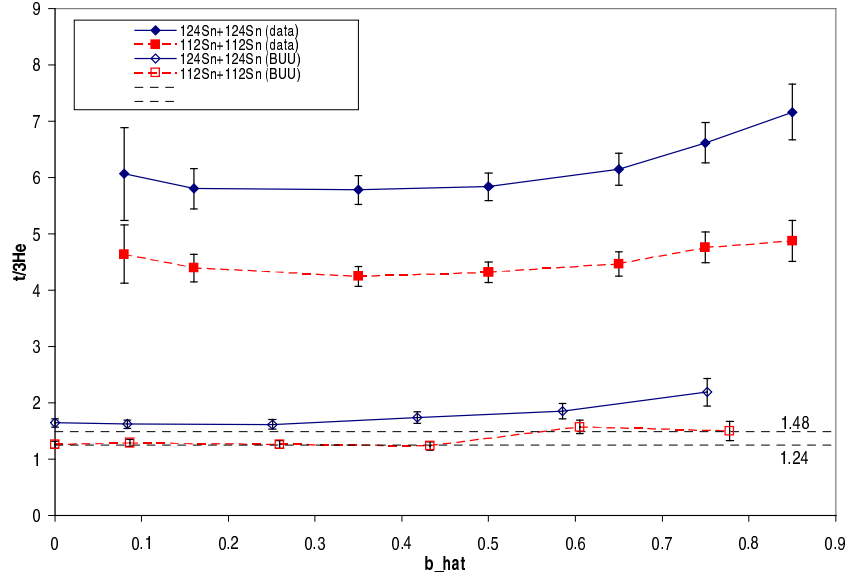
Figure 5. Comparison of t/^{3}He ratios for the central region as a function of b_hat between experimental collisions and BUU calculations.

The experimental measurement indicates that the BUU model cannot yet be used to explain heavy-ion collisions and formation of A = 3 clusters. One possible explanation is as follows. The formation of α-particles and heavier clusters (such as Li, Be, B, C, N, O) are neglected in the present BUU model and so the model does not account for a full phase transition. Qualitatively, these heavier clusters are composed of approximately the same number of protons and neutrons. The clusters with a larger number of protons/neutrons lead to a higher ratio of free neutrons relative to free protons. Therefore, a free n/p ratio is expected to be enhanced by an abundant emission of intermediate mass fragments (IMFs) with $3 \leq Z \leq 20$. In the BUU simulations, the effect of enhancing a free n/p ratio is absent because the BUU has no cluster production. Since t/^{3}He is related to free n/p ratio, it may be the reason for the large t/^{3}He ratios observed experimentally, but not reproduced by the calculations.

In summary, the microscopic BUU transport calculations suggests strong correlation between t/^{3}He and n/p ratio, however, the large magnitude of the experimental t/^{3}He yield ratio cannot yet be understood at the BUU model, which produces only light clusters $A \leq 3$. The failure is likely due to the neglect loss terms (α-particles and IMFs), which may lead to the formation of heavier clusters and enhancement of free neutrons as compared to protons, and therefore enhancement of the t/^{3}He ratio.

Further study of the effect of heavy fragment is needed. The dependence of isospin potential on the BUU model is currently being studied, however, exact conclusions cannot been drawn yet.

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