Transition in isospin behavior between light and heavy fragments emitted from excited nuclear systems

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The isospin dependence of light and heavy fragments emitted from excited nuclear systems and the change in isospin behavior between light and heavy fragments are studied in this report. The $\langle N/Z \rangle$ is calculated using data reported in the literature and from the results of the simulation code SMM. A transition in the isospin behavior between light and heavy fragments may support the recently reported two-phase bifurcation of excited nuclear matter into a neutron-rich gas phase and a more symmetric liquid phase.

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Complete understanding and characterization of the nuclear equation of state poses a challenge to nuclear physicists and chemists. One interesting dimension of the equation of state is the isospin degree of freedom of excited nuclear matter. For a review of isospin physics, look to that by Li and Ko [1]. Much work has been done studying the dependence of multifragmentation on isospin [2–6]. The isospin dependence of collective flow [7–10] has been looked at, as well. Odd-even effects in the trend of the isospin of fragments' dependence on the charge of the fragments have been seen in other studies [11,12]. Interest has recently been shown in the signatures of a two-phase split of excited nuclear matter into a neutron-rich, less dense phase and a more symmetric dense phase [13–17]. The current study reports on trends observed in the neutron to proton ratio seen in fragments emitted from excited nuclear systems and the transition seen between the isospin behavior of light and heavy fragments. The neutron to proton ratio is calculated using data reported in the literature of isotopically resolved fragments emitted from various excited nuclear systems and from the results of the simulation code SMM [18].

Müller and Serot of Indiana University put forth the idea that the phase transition associated with excited asymmetric nuclear systems is second order, with the added parameter involving the proton content of the excited matter [13]. Müller and Serot show that it is more energetically favorable for neutron rich, excited nuclear matter to bifurcate into a liquid phase which is more symmetric in isospin than the composite system and a gas phase containing excess neutrons. This separation of excited nuclear matter into two phases that differ in isospin will affect the fragmentation process. This effect may be observed by looking to experimental data for the neutron content of fragments and how they differ between light and heavy fragments. If excited nuclear matter is separating into two phases differing in isospin content, then light fragments may condense from the neutron rich gas and heavy fragments may evaporate off of the more symmetric liquid. This would result in light fragments being more neutron rich than heavier fragments. Recent results have indicated an enhancement of neutron richness in a gas phase by looking at ratios of light charged particle yields and how they differ with the isospin content of the compound system [14,19]. Let us look at an example of the effect on fragmentation of separation into phases with different neutron content. A trend of the average neutron to proton value decreasing with increasing mass number should be apparent, if the above picture is correct. Using helium as an example, the average neutron to proton value is calculated as follows, where ^{3}He is the number of ^{3}He detected or the cross section determined and likewise for the other helium isotopes:

$$\langle N/Z \rangle_{\mathrm{He}} = \frac{^3\mathrm{He} + 2 * {}^4\mathrm{He} + 4 * {}^6\mathrm{He}}{2 * ({}^3\mathrm{He} + {}^4\mathrm{He} + {}^6\mathrm{He})}. \tag{1}$$

There are examples in the literature that suggest that the expected trend of neutron-rich light fragments and more symmetric heavier fragments exists. Figure 1 shows the $\langle N/Z \rangle$ of fragments emitted from the reaction of a high-energy proton with Xe reported by the Purdue group [20] as calculated using the above equation and plotted as a function of Z. The energy of the proton on the Xe reaction is 80–350 GeV. Fragments were detected by two telescopes, one at 34°, consisting of three time-of-flight (TOF) detectors, a gas ionization detector, and a silicon detector, the other at 76°, consisting of three TOF detectors and a series of dE, dE, E silicons. Data were reported in terms of isotopically resolved normalized differential cross sections. If excited nuclear matter is bifurcating into a neutron-rich gas and a more symmetric liquid, then light fragments would have enhanced neutron content, leaving the heavy fragments with a comparatively lower neutron content. One can observe a trend in the $\langle N/Z \rangle$ values that begins high at low Z and levels out toward higher Z. This transition in isospin behavior between light and heavy fragments supports the idea of the two-phase split of excited nuclear matter. The error bars shown on the experimental data in the top panel of Fig. 1 reflect only systematic errors reported in the literature.

The proton on Xe reaction was modeled using the statistical code SMM [18]. The initial conditions of SMM were set

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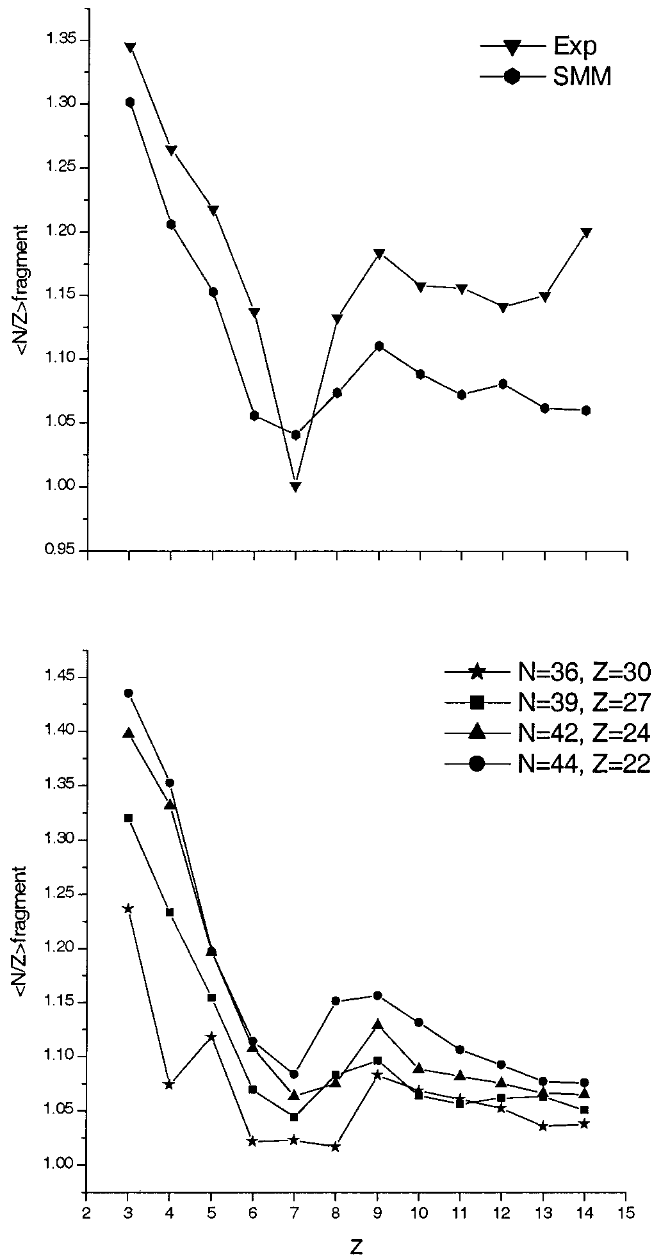

FIG. 1. The average neutron to proton ratio (top panel) as a function of Z for the reaction of 80–350 GeV H on Xe [20]. SMM predictions (bottom panel) for a simulation of a subsystem with different isospin contents.

to reflect the total mass and charge of the target and projectile of the system and the total transfer of kinetic energy of the projectile into the compound system. The outputs from the code were fed through a filter that matched the energy thresholds and angle of detection of the experimental setup. SMM matches the trend well in the proton on Xe system, as seen in the top panel of Fig. 1, but underestimates the $\langle N/Z \rangle$ values. It is interesting to look at what trends SMM predicts in the $\langle N/Z \rangle$ for fragments emitted from subsystems with various isospin content. The bottom panel of Fig. 1 shows the results of SMM, predicting the fragment isospin dependence of four different sources with different isospin content. The four different initial subsystems all have an initial constant

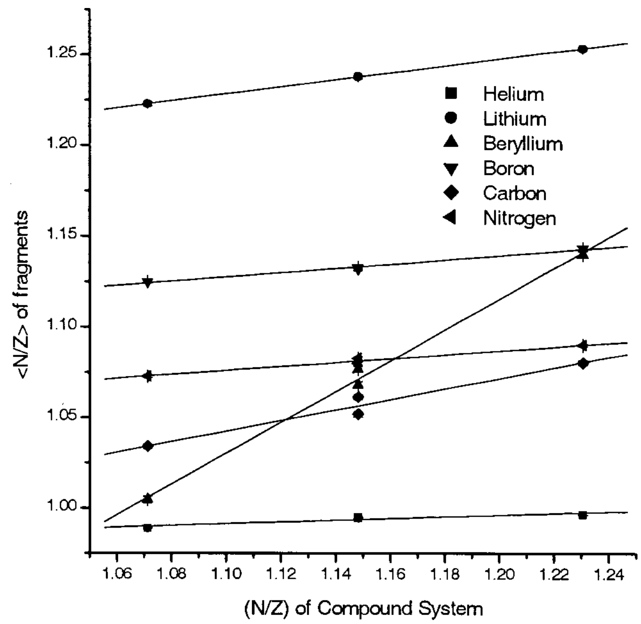

FIG. 2. The isospin dependence of emitted fragments from the mixed and symmetric reactions of ^{58}Fe, ^{58}Ni+^{58}Fe, ^{58}Ni at 30 MeV per nucleon on the N/Z of the compound system.

mass of 66, which represents an equal split of the mass of the initial compound system into two phases. The subsystems contain varying numbers of neutrons and protons ranging from 36 neutrons and 30 protons to 44 neutrons and 22 protons. As the emitting source becomes less neutron rich, SMM predicts a decrease in the isospin content of lithium fragments of 11.5% while the isospin content of silicon fragments only decreases by 2.59%. This SMM-predicted trend in the isospin content of the emitted fragments also supports the idea of the two-phase split of excited nuclear matter into a less dense neutron rich phase and a more dense and isospin symmetric phase. Additionally, as the initial compound system is set to be more and more neutron rich, lighter fragments emitted from the system display more neutron richness and the heavier fragments show less neutron-richness. The error bars on all SMM predictions are smaller than the data points.

Other trends are observed in the neutron to proton ratio of fragments emitted from excited systems. The average neutron to proton ratio of fragments emitted from excited nuclear systems is seen to vary with the neutron to proton ratio of the compound system. In the work performed by Ramakrishnan [21], depicted in Fig. 2, the energy, angle of detection, and total A of the system are all held constant, while varying the $\langle N/Z \rangle$ of the compound system. The system studied in Fig. 2 involves ^{58}Fe, ^{58}Ni+^{58}Fe, and ^{58}Ni at 30 MeV per nucleon. The fragments' isospin show a proportional dependence on the N/Z of the system. Beryllium shows a heightened dependence on the compound system isospin, which will be briefly discussed later. The trends shown in the data in Fig. 2 will be used as a base line to investigate the dependence of fragments' isospin on the size of the compound system in data that has varying compound mass and isospin.

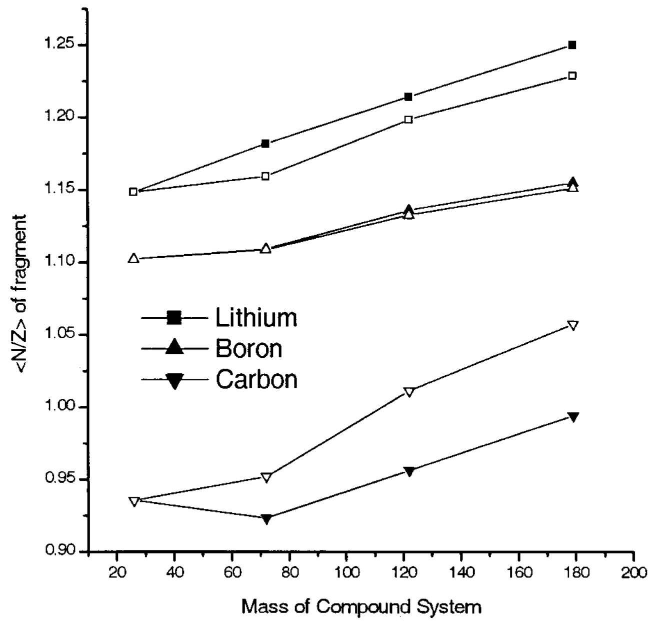

FIG. 3. The isospin dependence on the total mass of the compound system from the reactions of ^{14}N on C, Ni, Ag, Ho at 35 MeV/nucleon. The calculated dependence on the N/Z of the compound system as defined from data in Fig. 2 is shown as dashed lines.

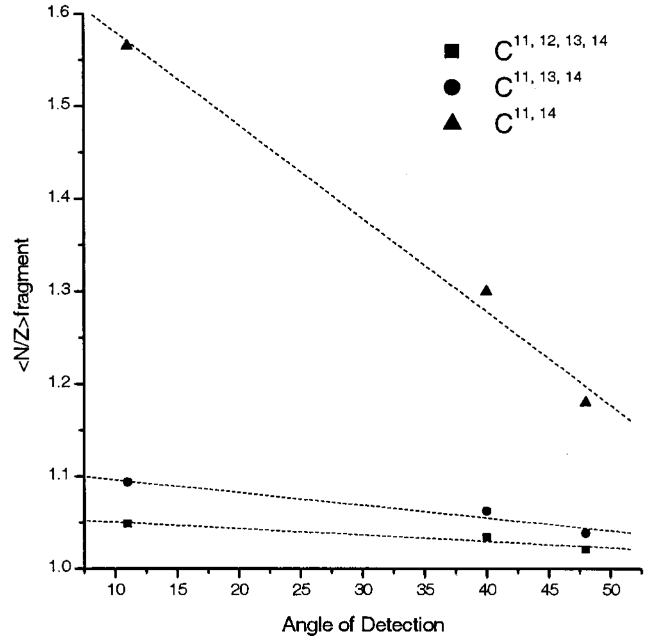

FIG. 4. The enhanced dependence of $\langle N/Z \rangle$ of carbon from the reaction of 30 MeV/nucleon ^{58}Ni on ^{58}Ni as the most abundant isotopes are excluded from the $\langle N/Z \rangle$ calculation.

Figure 3 shows that the $\langle N/Z \rangle$ content of fragments varies with the total mass of the compound system for the reaction of 35 MeV/nucleon ^{14}N beam onto four targets ^{12}C, ^{58}Ni, ^{165}Ho, and ^{108}Ag [22]. Fragments were detected from 15° to 83°. Data were reported in terms of isotope yield ratios, which were all set equal to 1000 counts and solved for the number of counts for each isotope. These counts were plugged into the equation shown earlier to obtain an $\langle N/Z \rangle$ value for each fragment charge detected. Each pair of lines in Fig. 3 represents a different fragment charge. All fragments show some dependence on the total A of the compound system. In these data by Deak and Kiss, both the total mass of the system and the N/Z of the system vary. However, in the previous data, the total mass of the system is held constant, while only the N/Z of the compound system varies. This raises the questions of how much of the dependence of the fragments' $\langle N/Z \rangle$ in the Deak-Kiss data is due solely to the change in the N/Z of the compound system and how much is due to the mass of the system. In an effort to answer this question, a linear fit was made to the trends in Fig. 2 in order to predict the fragments' $\langle N/Z \rangle$ dependence that is solely due to the N/Z of the compound system. This dependence on the N/Z of the compound system in Fig. 2 is only fit for the following values of N/Z of the compound system: $1.07 < N/Z$ of the compound system < 1.23. The N/Z of the compound system in the Deak-Kiss example varies from 1.00 to 1.32. The calculated values of the fragments' $\langle N/Z \rangle$ dependence on N/Z of the compound system are shown in Fig. 3 with open symbols. Each calculated line is normalized to the first experimental point. In the case of lithium, the $\langle N/Z \rangle$ dependence on the N/Z of the compound system is less than that seen in the mass dependent experimental data. On the other hand, carbon has a predicted dependence on the N/Z of the compound system that is larger than that seen in the mass dependent experimental data. This represents a transition whereby the lightest fragments are showing a larger dependence on the mass of the system than the heavier fragments, which are showing less neutron richness than predicted solely on the change in the N/Z of the compound system. This is consistent with the picture of the light elements condensing out of a neutron-rich gas while the heavier elements are originating from a more symmetric liquid.

The exaggerated dependence of the $\langle N/Z \rangle$ of Be on the N/Z of the compound system could be explained by the absence of ^{8}Be. For a rough comparison, the data taken in Ref. [21] for the 30 MeV/nucleon ^{58}Ni on ^{58}Ni are plotted as a function of angle for subsets of the isotopes of carbon detected (Fig. 4). In one instance, all isotopes are included in the $\langle N/Z \rangle$ calculation. In the other two examples shown in Fig. 4, ^{12}C and then both ^{12}C and ^{13}C are taken out of the $\langle N/Z \rangle$ calculation. As the most abundant isotopes of carbon are excluded from the reaction, the slope or dependence of the $\langle N/Z \rangle$ of carbon fragments on the angle of detection increases rapidly. Therefore, the enhanced dependence of Be on the N/Z of the compound system may be partly explained by the absence of ^{8}Be.

In summary, the average neutron to proton ratio of fragments emitted from excited nuclear systems is seen to change with isospin of the compound system and with the size of the fragment emitted. That trend in the $\langle N/Z \rangle$ of these fragments is shown to have higher $\langle N/Z \rangle$ values in lighter fragments and subsequently lower $\langle N/Z \rangle$ values in heavier fragments. Beryllium displays an exaggerated dependence, which may be explained by the absence of detection of ^{8}Be. These data are consistent with a two-phase bifurcation of excited nuclear matter into a more symmetric liquid and a neutron rich gas proposed by Müller and Serot. The trend observed in the $\langle N/Z \rangle$ ratios of fragments emitted from excited nuclear systems is inconsistent with any cold fragmentation models.

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