Investigation of the nuclear phase transition using the Landau free energy approach

J. Mabiala, A. Bonasera, H. Zheng, A.B. McIntosh, L.W. May, P. Cammarata, Z. Kohley, K. Hagel, L. Heilborn, A. Zarrella, A. Raphelt, and S.J. Yennello

Nuclear multifragmentation is one of the most interesting phenomena in heavy-ion collisions, for studying the behavior of nuclear matter under extreme conditions of temperature and density, and possible phase transitions. In recent works [1,2,3] fragment yields have been used to investigate the nuclear liquid-gas phase transition using the Landau free energy approach, which is applicable to systems in the vicinity of a critical point. In the Landau free energy approach, the isospin asymmetry of a fragmenting source acts as an external field which can modify the fragment yields. In the present work, fragment yield data from ^{64}Zn +^{64}Zn, ^{64}Ni+ ^{64}Ni and ^{70}Zn +^{70}Zn reactions at 35 MeV/nucleon were analyzed within the framework of the Landau free energy approach.

The experiment was performed at the Texas A&M University Cyclotron Institute. Charged particles were measured using the NIMROD-ISiS 4π detector array, which was housed inside the TAMU Neutron ball. Details on the experiment are reported in Ref. [4]. In the analysis, quasi-projectile (QP) sources were reconstructed and selected by means of event-by-event cuts as in Ref. [5]. The QP mass was restricted to be in the range $54 \leq A \leq 64$. Its excitation energy was deduced using the measured free neutron multiplicity, the charged particle kinetic energies, and the Q-value of the breakup. Data were sorted into four different bins in QP source asymmetry ($m_s = (N - Z)/A$) ranging from 0.04 to 0.24 with bin width of 0.05. Effects of QP excitation energies on the thermodynamic quantities were investigated by gating the data into nine bins of 1 MeV in the range of 1-10 MeV/nucleon.

In the modified Fisher model, the fragment yield near the critical point is related to its free energy (F) normalized with respect to the temperature T by [6]

$$Y = y_0 A^{-\tau} e^{-\frac{F}{T} A} \tag{1}$$

with y_0 a constant, A the fragment mass number and τ a critical exponent. In the Landau approach, F/T can be written in terms of an order parameter m as given by [6]

$$\frac{F}{T} = \frac{1}{2} a m^2 + \frac{1}{4} b m^4 + \frac{1}{6} c m^6 - \frac{H}{T} m \tag{2}$$

The parameters a, b and c contain information about the position of the fragmenting system with respect to the critical point. H is the external field due to the isospin asymmetry of the source (m_s). In the absence of any external field $(H/T=0)$, Eq. (2) may predict three minima with $m=0$ the central minimum. The presence of an external field shifts the positions of these minima.

The free energy data were obtained by normalizing fragment yields with respect to ^{12}C yields to eliminate the constant y_0. F/T values of $N=Z$ nuclei were observed to significantly deviate from the regular behavior of the $N \neq Z$ fragments. These so-called odd-even effects were corrected by a pairing coefficient extracted from the analysis of N=Z fragments. The following equation was used for the fragment yield to correct for pairing effects

$$Y = y_0 A^{-\tau} e^{-\left(\frac{F}{T}-\frac{a_p}{T}\frac{\delta}{A^{3/2}}\right)A} \tag{3}$$

where a_p is the pairing coefficient. Fig. 1 shows free energy *(F/T)* values for different for different m_s bins. Solid lines (Fit1) are fit to the data using the Landau free energy (Eq. 2) with *a, b, c and H/T* as free parameters. Dashed lines (Fit2) are fit to data using only first and last terms of Eq. (2). It is seen from the figure that the Landau equation provides a better fit to the free energy data. The three minima seen in the free energy plot indicate the system to be in the regime of a first order phase transition. However, a more definitive conclusion on this aspect would require measurement of exotic fragments with large m to better constrain the fit.

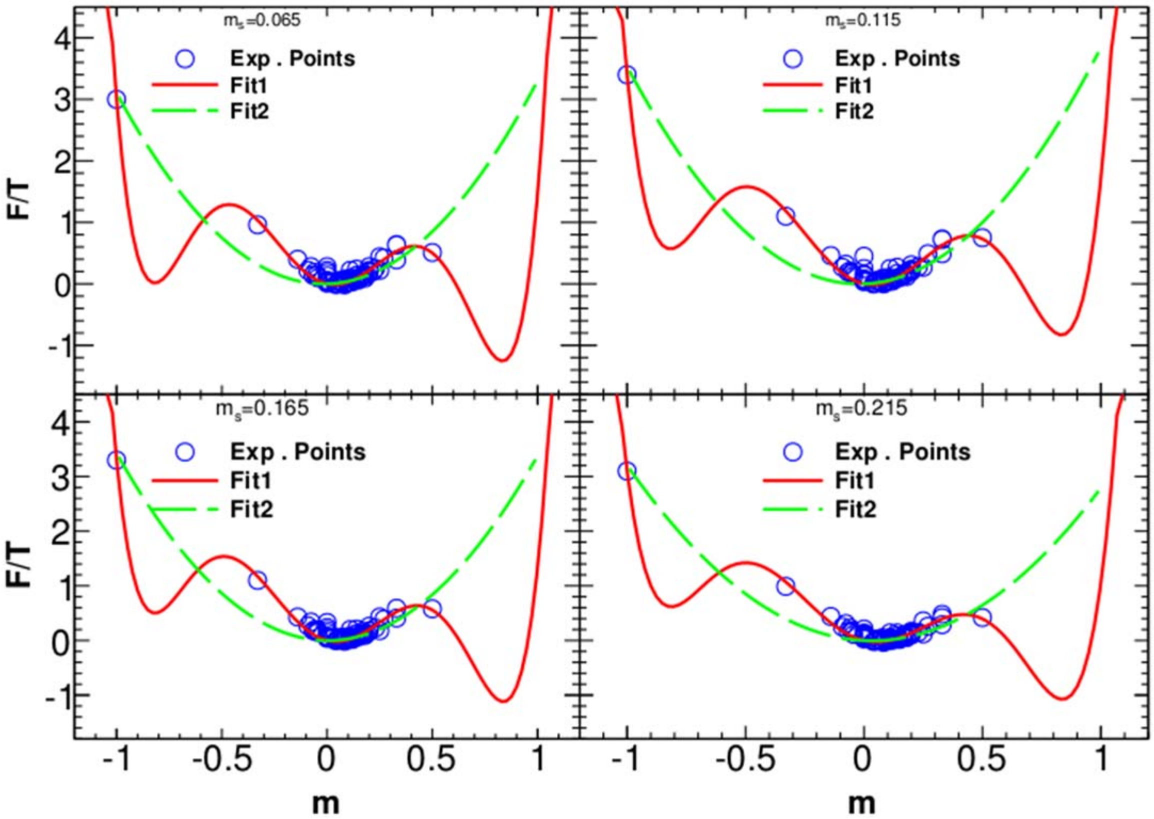

FIG. 1. F/T as a function of fragment isospin asymmetry m. Different panels correspond to different source asymmetry (m_s) bins.

In Fig. 2, the a_p/T values extracted for different m_s bins are plotted as a function of the QP excitation energy. It is observed that a_p/T values systematically decrease with increasing QP excitation energy. These a_p/T values are used to estimate the temperature of the QP for each m_s bin assuming a_p=12

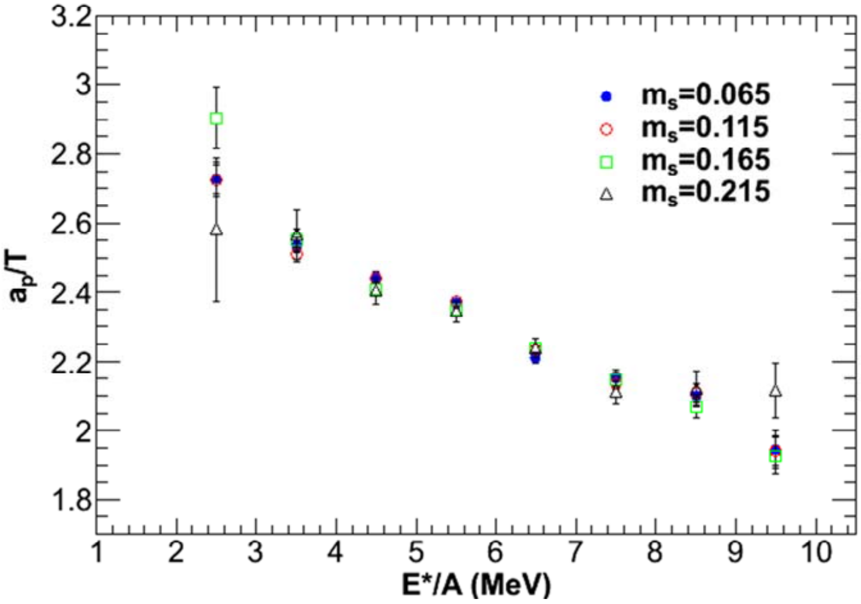

FIG. 2. a_p/T as a function of the QP excitation energy (E*/A) for different bins in source asymmetry.

MeV. The fitting parameters a, b, c and H/T extracted for each m_s bin are plotted versus the QP excitation energy in Fig.3. The parameters a, b and c which are related to thermodynamic properties of the fragmenting system show a dependence on m_s in addition to their dependence on the excitation energy. H/T shows a systematic increase with increasing m_s. This verifies qualitatively that the external field H is the conjugate variable of m_s. The parameters a, b and c are very close to satisfying the condition for a first order phase transition $b = -4\sqrt{ac/3}$.

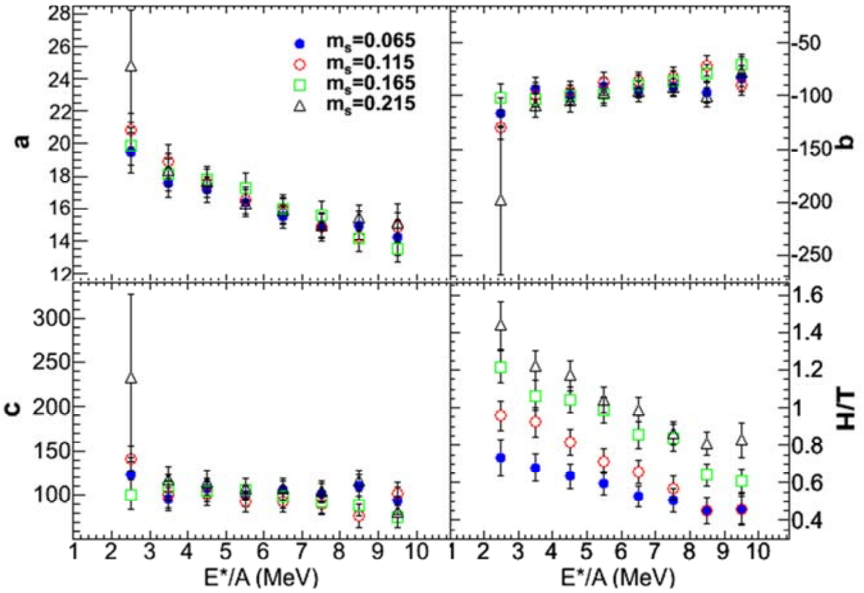

FIG. 3. Fitting parameters a, b, c and H/T obtained from fits to the free energy data as a function of E*/A for different bins in m_s.

In summary, a detailed analysis of the data on fragment yields within the framework of the Landau free energy approach showed the signature of a first-order phase transition with respect to isospin asymmetry of the fragmenting source. Future work will be to complement these results and temperatures and densities extracted from the new quantum method by Zheng and Bonasera [7, 8].

[1] A. Bonasera *et al.*, Phys .Rev .Lett. **101**, 122702 (2008).
[2] M. Huang *et al.*, Phys. Rev. C **81**, 044618 (2010).
[3] R. Tripathi *et al.*, Phys. Rev. C **83**, 054609 (2011).
[4] Z. Kohley, PhD Thesis, Texas A&M University, 2010.
[5] S. Wuenschel *et al.*, Nucl. Phys. **A843**, 1 (2010).
[6] R. Tripathi *et al.*, Int. J. Mod. Phys. E **21**, 1250019 (2012).
[7] H. Zheng and A. Bonasera, Phys.Lett. B **696**, 178 (2011).
[8] H. Zheng and A. Bonasera, (2011), nucl-th/1112.4098.