Towards the critical behavior for the light nuclei by NIMROD detector

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The critical behavior for the light nuclei with A$\sim$ 36 has been investigated experimentally by the NIMROD multi-detectors. The wide variety of observables indicate the critical point has been reached in the disassembly of hot nuclei at an excitation energy of 5.6$\pm$0.5 MeV/u.

1. INTRODUCTION

Most efforts to determine the critical point for the expected liquid gas-phase transition in finite nucleonic matter have focused on examinations of the temperature and excitation energy region where maximal fluctuations in the disassembly of highly excited nuclei are observed [1, 2, 3, 4]. Fisher Droplet Model analyses have been applied to extract critical parameters which are very close to those observed for liquid-gas phase transitions in macroscopic systems [5]. In previous studies on liquid gas phase change, attention focused mostly on the larger atomic nuclei. However, the larger Coulomb effects make it difficult to reach the critical point of the finite nucleonic matter. In contrary, it was suggested that the decreasing importance of Coulomb effects makes the lightest nuclei the most favorable venue for investigation of the critical point [6].

In this paper, we report results of an extensive investigation of nuclear disassembly in nuclei of $A \sim 36$ excited to energies as high as 9 MeV/u and many observables are related to the critical behavior at an excitation energy of 5.6±0.5 MeV.

2. RESULTS AND DISCUSSIONS

Using the TAMU NIMROD detector and beams from the TAMU K500 Super-conducting Cyclotron, we have probed the properties of excited quasi-projectile (QP) fragments produced in the reactions of 47 MeV/u ^{40}Ar + ^{58}Ni. Earlier work on systems at energies near the Fermi energy have demonstrated the essential binary nature of such collisions, even at relatively small impact parameters. As a result, these collisions prove to be very useful in preparing highly excited light nuclei.

The charged particle detector array of NIMROD which is set inside a neutron ball includes 166 individual CsI detectors arranged in 12 rings in polar angles from $\sim 3^\circ$ to $\sim 170^\circ$. In these experiments each forward ring included two super-telescopes composed of two Si-Si-CsI detectors and three Si-CsI telescopes to identify intermediate mass fragments. In the CsI detector H and He isotopes are clearly identified and Li fragments are also isolated from the heavier fragments. In the super-telescopes, all isotopes with atomic number $Z \leq 8$ are clearly identified and in all telescopes particles are identified by atomic number. The NIMROD neutron ball, which surrounds the charged particle array, was used to determine the neutron multiplicities for selected events. The correlation of the charged particle multiplicity and the neutron multiplicity was used to select violent collisions.

A new method to reconstruct QP has been developed in this work. We first obtain the laboratory energy spectra for different LCP at different laboratory angles and reproduce them using the three source fits, *i.e.* the QP, NN and QT sources. From these fits we know the relative contributions from the QP, NN and QT sources. Employing this information to determine the energy and angular dependent probabilities we analyze the experimental events once again and, on an event by event basis, use a Monte Carlo sampling method to assign each LCP, *i.e.*, to one of the sources QP, or NN, or QT. For intermediate mass fragments (IMF) with Z≥4, we have used a rapidity cut ($>$ 0.65 beam rapidity) to assign IMF to the QP source. Once we have identified all LCPs and IMFs which are assumed to come from the QP source, we can reconstruct the whole QP source on an *event-by-event* basis. For the present analysis we have selected reconstructed QP events with total charge number $Z_{QP} \geq 12$ from violent collisions. The QP source velocity was determined from momentum conservation of all QP detected particles. The excitation energy distribution was deduced using the energy balance equation.

The Fisher droplet model has been extensively applied to the analysis of multifragmentation. It predicts that relative yields of fragments with $3 \leq Z \leq 14$ could be well described by a power law dependence $A^{-\tau}$ when the liquid gas phase transition occurs and τ value is the minimum in that point. In Fig. 1 we present, for the QP from the reactions of ^{40}Ar + ^{58}Ni, yield distributions, dN/dZ, observed for our nine intervals of excitation energy. At low excitation energy a large Z residue always remains, *i.e.* the nucleus is basically in the liquid phase accompanied by some evaporated light particles. When E^*/A reaches ~ 6.0 MeV/u, this residue is much less prominent. As E^*/A continues to increase, the charge distributions become steeper, which indicates that the system tends to vaporize. To quantitatively pin down the possible phase transition point, we use a power law fit to the QP charge distribution in the range of Z = 2 - 7 to extract the effective Fisher-law parameter τ_{eff} by $dN/dZ \sim Z^{-\tau_{eff}}$. The Fig. 2(a) shows τ_{eff} vs excitation energy, a minimum with $\tau_{eff} \sim 2.3$ is seen to occur in the E^*/A range of 5 to 6 MeV/u. $\tau_{eff} \sim 2.3$, is close to the critical exponent of the liquid gas phase transition universality class as predicted by Fisher's Droplet model [5]. The observed minimum is rather broad. While, assuming that the heaviest cluster in each event represents the liquid phase, we have attempted to isolate the gas phase by event-by-event removal of the heaviest cluster from the charge distributions. We find that the resultant distributions are better described as exponential form $exp(-\lambda_{eff} Z)$. The fitting parameter λ_{eff} was derived and is plotted against excitation energy in Fig. 2(b). A minimum is seen in the same region where τ_{eff} shows a minimum.

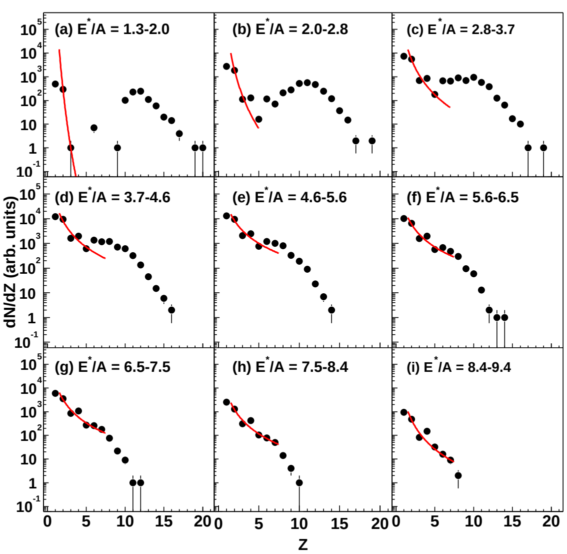

Figure 1. Charge distribution of QP in different E^*/A window for the reaction ^{40}Ar + ^{58}Ni. Lines represent fits.

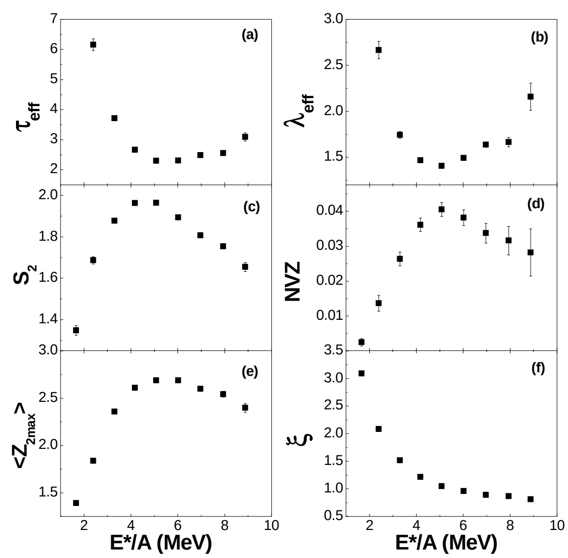

Figure 2. The effective Fisher-law parameter (τ_{eff}) (a), the effective exponential law parameter (λ_{eff}) (b), $\langle S_2 \rangle$ (c), NVZ fluctuation (d), the mean charge number of the second largest fragment $\langle Z_{2max} \rangle$ (e), the Zipf-law parameter ξ (f). See details in text.

To further explore this region we have investigated other proposed observables commonly related to fluctuations and critical behavior. Fig. 2(c) shows the mean normalized second moment [1], $\langle S_2 \rangle$ as a function of excitation energy. A peak is seen around 5.6 MeV/u, it indicates that the fluctuation of the fragment distribution is the largest in this excitation energy region. Similarly, the normalized variance in Z_{max}/Z_{QP} distribution (i.e. NVZ $= \frac{\sigma^2_{Z_{max}/Z_{QP}}}{\langle Z_{max}/Z_{QP} \rangle}$) [7] shows a maximum in the same excitation energy region [Fig.

2(d)], which illustrates the maximal fluctuation for the largest fragment (order parameter) is reached around $E^*/A = 5.6$ MeV. Except the largest fragment, the second largest fragment also shows its importance in the above turning point. Fig. 2(e) shows a broad peak of $\langle Z_{2max} \rangle$ - the average atomic number of the second largest fragment exists at 5.6 MeV/u.

The significance of the 5-6 MeV region in our data is further indicated by a Zipf's law analysis proposed by Ma [8]. In such an analysis, the cluster size is employed as the variable to make a Zipf-type plot. We can define a Zipf-type plot by plotting the mean sizes of fragments which are rank-ordered in size, i.e., largest, second largest, etc. as a function of their rank [8]. The resultant distributions are fitted with a power law, $\langle Z_{rank} \rangle \propto rank^{-\xi}$, where ξ is the Zipf's law parameter. When $\xi \sim 1$, Zipf's law is satisfied. In this case, the mean charge of the second largest fragment is 1/2 of that of the the largest fragment; that of the third largest fragment is 1/3 of the largest fragment, etc. This is a kind of special topological fragment structure. By the fits we obtained parameters ξ as a function of excitation energy as shown in Fig.2(e). This rank ordering of the probability observation of fragments of a given atomic number, from the largest to the smallest, does indeed lead to a Zipf power law parameter $\xi \sim 1$ in the 5-6 MeV/u range.

The calculations of the phase transition models, namely the lattice gas model (LGM) and statistical multifragmentation model (SMM), show very similar behavior as the experimental data in Fig.1 and 2. But the sequential decay model fails. This indicates that the data around $E^*/A = 5.6$ MeV/u can be actually explained by the phase change [9].

3. SUMMARY

In our measurements for the disassembly of small nucleui with A $\sim$ 36, the maximal fluctuations are observed at 5.6 ± 0.5 MeV/u excitation energy. Also the fragment topological structures suggest the onset of a phase change. Comparisons with results of LGM and SMM calculations suggest that the critical point may have been reached. Taken together, this body of evidence suggests a phase change at, or extremely close to, the critical point of this light nuclear system.

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