Excitation Energy as a Basic Variable to Control Nuclear Disassembly

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Thermodynamical features of Xe system is investigated as functions of temperature and freeze-out density in the frame of lattice gas model. The calculation shows different temperature dependence of physical observables at different freeze-out density. In this case, the critical temperature when the phase transition takes place depends on the freeze-out density. However, a unique critical excitation energy reveals regardless of freeze-out density when the excitation energy is used as a variable insteading of temperature. Moreover, the different behavior of other physical observables with temperature due to different \(\rho_f\) vanishes when excitation energy replaces temperature. It indicates that the excitation energy can be seen as a more basic quantity to control nuclear disassembly.

The phase transition and critical phenomenon of small systems is an interesting subject in recent nuclear physics research. The break-up of nuclei due to violent collisions into several intermediate mass fragments (IMF), can be viewed as critical phenomenon as observed in fluid, atomic, and other systems. It prompts the possible signature on the liquid gas phase transition of the nuclear system. On one hand, the onset of the multifragmentation and vaporization channels can be seen as the signature of the boundaries of phase mixture. This is supported further by the fact that the caloric curve in a certain excitation energy range shows a saturate similar to a first order phase transition, in the framework of statistical equilibrium models. On other hand, the observation of critical exponents parameters in the charged or mass distribution of the multifragmentation system can be interpreted as an evidence of the phase transition. Recently, the lattice gas model (LGM) has been applied to treat phase transition and critical phenomenon in the nuclear disassembly for isospin symmetrical and asymmetrical nuclear systems. LGM assumes a freeze-out density \(\rho_f\) with thermal equilibrium at temperature \(T\). The temperature was adopted naturally as a variable to study the feature of disassembly in nearly all previous calculation of LGM. In this paper, we will illustrate that the excitation energy can be taken as a more basic quantity to control the disassembly of nuclear system rather than temperature via studying the features of critical phenomenon and other physical observables in the lattice gas model.

In the lattice gas model, \(A\) nucleons with an occupation number \(s\) which is defined as \(s = 1\) for a proton (neutron) or \(s = 0\) for a vacancy, are placed in the \(L\) sites of lattice. Nucleons in the nearest neighbouring sites have interaction with an energy \(\epsilon_s s_j\). The hamiltonian is written by \(E = \sum_{i=1}^{A} \frac{P^2_i}{2m} - \sum_{i<j} \epsilon_s s_i s_j\). The interaction constant \(\epsilon_s\) is related to the binding energy of the nuclei. Here \(\epsilon_{nn,pp} = \epsilon_{-1-1,11,11} = -0.53\) MeV is used. The freeze-out density of disassembling system is \(\rho_f = \frac{4}{3}\rho_0\) where \(\rho_0\) is the normal nucleon density. The disassembly of the system is to be calculated at \(\rho_f\), beyond which nucleons are too far apart to interact. \(N + Z\) nucleons are put in \(L\) cubes with size \(l^3\) by Monte Carlo sampling using the Metropolis algorithm. Once the nucleons have been placed, their momentum is generated by a Monte Carlo sampling of Maxwell Boltzmann distribution. Various observables can be calculated in a straightforward fashion.

One of the basic measurable quantities is the distribution of fragment mass. In this LGM, two neighboring nucleons are viewed to be in the same fragment if their relative kinetic energy is insufficient to overcome the attractive bond: \(P^2_i/2\mu + \epsilon_{np} < 0\). Once the fragment mass distribution is built, we can extract the effective power law parameters via fitting the mass distribution of fragments with \(Y(A_i) \propto A_i^{-\tau}\) and its second moment of fragment distribution defined

\begin{equation} \tag{1} b_D = \frac{1}{n} \sum_{i=1}^{n} \frac{b_{D,i}}{\epsilon_{s,i,j}} \end{equation} 

\begin{equation} \tag{2} \mu = \frac{1}{n} \sum_{i=1}^{n} \frac{\mu_i}{(A_i)} \end{equation} 

\begin{equation} \tag{3} c_{T} = \frac{1}{n} \sum_{i=1}^{n} \frac{c_{T,i}}{(A_i)^2} \end{equation} 

\begin{equation} \tag{4} \epsilon_{np} = \frac{1}{n} \sum_{i=1}^{n} \frac{\epsilon_{np,i}}{(A_i)^3} \end{equation} 

\begin{equation} \tag{5} \rho_f = \frac{4}{3}\rho_0 \end{equation}
as 
\[ S2 = \sum_{i,j\neq A_{max}} \frac{A_i^2 + n_i(A_i)}{A_{max}} \]
where \( n_i(A_i) \) is the number of fragments with \( A_i \) nucleons and the sum excludes the largest cluster \( A_{max} \).
There are a minimum of \( \tau \) and a maximum of \( S2 \) at critical point for an infinite system. Besides the above quantities, we will use the average multiplicity \( < IMF > \) of IMF and the information entropy \( H \) to search the critical point. \( H \) was defined firstly by Shannon in information theory and can be introduced into nuclear dissociation of \( T \), it reads \( H = -\sum_i p_i \ln(p_i) \), where \( p_i \) is the probability having \( "i" \) produced particles in each event, the sum is taken over all multiplicities of products from the disassembling system. \( H \) reflects the capacity of the information or the extent of disorder.

We choose the medium size nuclei \( ^{129}\text{Xe} \) as an example to analyze the nuclear disassembly. Three freeze-out densities of 0.18\( \rho_0 \), 0.38\( \rho_0 \), and 0.60\( \rho_0 \), corresponding to the lattice size of 9\( ^3 \), 7\( ^3 \) and 6\( ^3 \) respectively, were used. The calculations were performed from 3 MeV to 7 MeV and 1000 events were accumulated at each temperature and freeze-out density.

We show the temperature and freeze-out density dependences of \( \tau \), \( < IMF > \), \( H \) and \( S2 \) in the left column of Fig.1. First, the critical temperatures determined by the extreme values are the same for the same freeze-out density, indicating that same freeze-out density minimizes the discrepancies stemming from different freeze-out density. Again, the discrepancies stemming from different freeze-out density minimize when the excitation energy can be viewed as a more basic parameter in controlling the reaction dissociation.

In order to illustrate this point further, Fig.2 gives the average mass of the largest fragment \( A_{max} \), the isotopic ratio \( R(p/d) \) between protons and deuterons, the isobaric ratio \( R(t/\beta \text{He}) \) between tritons and helium-3 and the ratio \( R(n/p) \) of emitted neutrons to protons as a function of temperature or excitation energy, respectively, in different freeze-out density. Again, the discrepancies steming from different freeze-out density in experiments, especially in 4\( ^\pi \) multidetectors nowadays. Hence the use of excitation energy as a basic parameter will make it easier and definite to extract physics from the direct comparison between the experimental data and the theoretical calculation.

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Figure Captions

Fig.1: The observables as a function of temperature (the left column) or excitation energy (the right column) in different freeze-out density: the $\tau$ parameter from the power law fit to mass distribution (a,g), the average multiplicity of intermediate mass fragments $<IMF>$ (b,h), the information entropy $H$ (c,i) and the second moment $S_2$ (d,j). The mapping from temperature to excitation energy is plotted in Fig.1e and the specific heat is shown in Fig.1f.

Fig.2: The average mass of the largest fragment in each event $A_{max}$ (a,e), the isotopic ratio $R(p/d)$ between the protons and neutrons (b,f), the isobaric ratio $R(t/3He)$ between the tritons and the Helium-3 (c,g), and the ratio $R(n/p)$ of neutrons and protons (d,h). The left column is plotted versus the temperature $T$ and the right column versus the excitation energy.
Fig. 1
Fig. 2