Physics Letters B 783 (2018) 364–367

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

First-order derivative of cluster size as a new signature of phase transition in heavy ion collisions at intermediate energies

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ARTICLE INFO

Article history:
Received 22 March 2018
Received in revised form 5 July 2018
Accepted 6 July 2018
Available online 11 July 2018
Editor: J.-P. Blaizot

ABSTRACT

The phenomenon of liquid-gas phase transition occurring in heavy ion collisions at intermediate energies is a subject of contemporary interest. Phase transition is usually characterized by the specific behaviour of state variables like pressure, density, energy etc. In heavy ion collisions there is no direct way of accessing these state variables and hence unambiguous detection of phase transition becomes difficult. This work establishes that signatures of phase transition can be extracted from the observables which are easily accessible in experiments and these have similar behaviour as the state variables. The temperature dependence of the first order derivative of the order parameters related to the largest and second largest cluster size (produced in heavy ion collisions) exhibit similar behaviour as that of the variation of specific heat at constant volume C_v which is an established signature of first order phase transition. This motivates us to propose these derivatives as confirmatory signals of liquid-gas phase transition. The measurement of these signals in easily feasible in most experiments as compared to the other signatures like specific heat, caloric curve or bimodality. This temperature where the peak appears is designated to be the transition temperature and the effect of certain parameters on this has also been examined.

1. Introduction

The study of liquid gas phase transition in heavy ion collisions has generated a lot of interest amongst the nuclear physicists in the recent years [1–6]. Different signatures of this transition have been studied extensively both theoretically [2,4–7] as well as experimentally [4–6]. First order phase transition is well characterized by some typical behaviour of different thermodynamic state variables like pressure, density, energy etc [8,9]. For example, the variation of excitation energy and specific heat with temperature are two theoretically well studied signatures in order to detect the first order phase transition [10–12]. The difficulty of accessing these state variables experimentally motivated us to look for more direct signatures of phase transition and in the recent papers [13,14] we have established the variation of derivative of multiplicity as a signature of liquid gas phase transition in nuclear multifragmentation. In this work we propose two new signatures of first order phase transition which can be measured more easily. The size of the largest cluster has already been established as an order parameter for first order phase transition in heavy ion collisions. Bimodal distribution of the order parameter at a certain temperature (or excitation energy) establishes the coexistence of two phases simultaneously and well studied both theoretically and experimentally [15–19]. Bimodality means two peaked distribution and the temperature where these peaks have equal height is identified as the transition temperature. There can be some ambiguity both experimentally and theoretically regarding the identification of equal heights of these peaks since the largest cluster distribution loose sharpness due to finite size of the system [20]. In view of this we propose a new signature related to the largest cluster size which can be identified much easily both theoretically as well as experimentally as compared to the bimodality of the largest cluster. The temperature dependence of first-order derivative of the largest cluster display similar behaviour as that of the specific heat at constant volume. Not only that both these variables also peak at the same temperature. We would like to emphasize that identification and determination of size of the largest cluster produced in fragmentation of hot nuclear system might be easier for the experiments as compared to the total multiplicity where is it required to detect all the fragments produced. In this respect this proposed new signature is of much greater significance as com-

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https://doi.org/10.1016/j.physletb.2018.07.012
0370-2693/

pared to the one proposed by us recently [13]. Another observable we have proposed here is related to the difference (normalized) between the sizes of the first and the second largest clusters which also serve as an order parameter for the phase transition in nuclear multifragmentation and is well studied experimentally [21,22]. The derivative of this also peaks at the same temperature as the specific heat and hence this can confirm the presence of liquid gas phase transition in nuclear multifragmentation as well. In this letter, we propose these two new signatures in order to establish the existence of liquid gas phase transition in heavy ion collisions and to determine the transition temperature as well.

We have used statistical models more specifically the canonical thermodynamical model (CTM) [23] in order to study the fragmentation of nuclei. In such models [3,23,24] of nuclear disassembly it is assumed that there statistical equilibrium is attained at freeze out stage and the population of different channels of disintegration is solely decided by statistical weights in the available phase space. The calculation is done for a fixed system size, freeze out volume and temperature. The total multiplicity, the average size of the largest and the second largest cluster are some of the observables calculated from this model which can be measured experimentally as well. As our primary interest here is to study phase transition in nuclear system owing to the nuclear force alone, like most theoretical models we have considered symmetric nuclear matter where the Coulomb interaction is switched off [25,26] (the Coulomb interaction being a long range one suppresses the signatures of phase transition) and there is no distinction made between neutron and proton.

We give a very brief description of the model and then present our results. Finally we will summarize and present the future outlook of this work.

2. Model description

In one component canonical model, we consider a system of A_0 nucleons disintegrating at constant temperature (T) and freeze-out volume (V_f). The partitioning into different composites is done such that all partitions have the correct A_0. The canonical partition function is given by

$$Q_{A_0} = \sum \prod \frac{(\omega_A)^{n_A}}{n_A!} \tag{1}$$

Here the product is over all fragments of one break up channel and sum is over all possible channels of break-up satisfying $A_0 = \sum A \times n_A$ where n_A is the number of composites of mass number A in the given channel and ω_A is the partition function of the composite having A nucleons. The partition function Q_{A_0} is calculated using a recursion relation [23,27]

The partition function of the composite ω_A is a product of two parts and is given by

$$\omega_A = \frac{V}{h^3}(2\pi mT)^{3/2} A^{3/2} \times z_A(int) \tag{2}$$

The first part is due to the translational motion and the second part $z_A(int)$ is the intrinsic partition function of the composite. V is the volume available for translational motion. Note that V will be less than V_f, the volume to which the system has expanded at break up. In general, we take V_f to be equal to three to six times the normal nuclear volume. We use $V = V_f - V_0$, where V_0 is the normal volume of nucleus with A_0 nucleons. The details of the model and properties of the composites used in this work are listed in details in [23].

Here we introduce briefly the observables of interest in our present work, one is the average size of the largest cluster A_{max} and other is a_2. Average size of the largest cluster is given as,

$$\langle A_{max} \rangle = \sum A_{max} \,.\, Pr(A_{max}) \tag{3}$$

where $Pr(A_{max})$ is the probability of getting a fragment of size A_{max} as the largest one. This probability is given as,

$$Pr(A_{max}) = \frac{\Delta Q_{A_0}(A_{max})}{Q_{A_0}(\omega_1, \omega_2, \omega_3, ..., \omega_{A_0})} \tag{4}$$

where,

$$\Delta Q_{A_0}(A_{max}) = Q_{A_0}(\omega_1, \omega_2, ..., \omega_{A_{max}}, 0, ..., 0) - Q_{A_0}(\omega_1, \omega_2, ..., \omega_{A_{max-1}}, 0, ..., 0) \tag{5}$$

This quantity $\Delta Q_{A_0}(A_{max})$ represents the total partition function in fragmentation of a system of size A_0, considering only those events where the size of the largest fragment is exactly A_{max} For the suitability of this work, we will use the parameter $a_{max} = \langle A_{max} \rangle / A_0$ which is the normalized size of the largest cluster (divided by the system size).

The normalized variable a_2 is $(\langle A_{max} \rangle - \langle A_{max-1} \rangle)/(\langle A_{max} \rangle + \langle A_{max-1} \rangle)$ [21,22], where $\langle A_{max-1} \rangle$ is the average size of the second largest fragment. One can calculate it, by proceeding in a similar way [16] of $\langle A_{max} \rangle$. Thus if $Pr_2(A_{max-1})$ is the probability for A_{max-1} to be the second largest fragment size, then

$$\langle A_{max-1} \rangle = \sum A_{max-1} \,.\, Pr_2(A_{max-1}) \tag{6}$$

Now, to get this probability, we see that A_{max-1} can be the second largest if (a) there is at least one fragment of size A_{max-1} and just one fragment of size $A_{max} > A_{max-1}$ or if (b) there are more than one fragment of size A_{max-1} but no fragment larger than it i.e. $A_{max} = A_{max-1}$. The partition function for the case (a) is

$$Q_a = \sum \omega_{A_{max}} \,.\, \Delta Q_{A_0 - A_{max}}(A_{max-1}) \tag{7}$$

where the sum goes from $(A_{max-1} + 1)$ to its maximum possible value and for the case (b) is

$$Q_b = \Delta Q_{A_0}(A_{max-1}) - \omega_{A_{max-1}} \,.\, Q_{A_0 - A_{max-1}}(\omega_1, \omega_2, ..., \omega_{A_{max-1}-1}, 0, ...) \tag{8}$$

The first term is the total partition function for the channels where the largest cluster size is A_{max-1} but the number of such clusters can be one or more. The second term gives the total partition function for the channels where the number of fragments of size A_{max-1} (i.e., largest cluster) is just one. So the difference is the partition function for case (b). Therefore, the second largest cluster probability will be,

$$Pr_2(A_{max-1}) = [Q_a + Q_b]/Q_{A_0} \tag{9}$$

Once we get the probability, using Eqn. (6) $\langle A_{max-1} \rangle$ can be calculated.

3. Results

The size of the largest cluster formed in the fragmentation of an excited nuclei behaves as an order parameter for first order phase transition [15,28–30]. The largest cluster size varies (decreases) very slowly as the temperature rises and then suddenly as the liquid-gas transition temperature is reached, there is a sudden fall in the largest cluster size after which it again decreases very slowly. This behaviour is depicted in Fig. 1(a). a_2 which represents the normalized size difference of the first and the second largest cluster also displays similar behaviour as a_{max} and that is shown in Fig. 1(b). This parameter is also markedly different in the