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Caloric curve in Au+Au collisions

C. B. Das and L. Satpathy
Institute of Physics, Bhubaneswar- 751 005, India
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Realistic caloric curves are obtained for the ^{197}Au+^{197}Au reaction with incident energy ranging from 35 to 130 MeV/nucleon in the dynamic statistical multifragmentation model. It is shown that for the excitation energy 3 to 8 MeV/nucleon, the temperature remains constant in the range 5 to 6 MeV, which is close to the experiment. The mechanism of energy deposition through the tripartition of the colliding system envisaged in this model together with interfragment nuclear interaction are found to play important roles. A possible signature of a liquid-gas phase transition is seen in the specific heat distribution calculated from these caloric curves, and the critical temperature is found to be ~6 to 6.5 MeV. [S0556-2813(98)50901-6]

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It has been speculated more than ten years ago that the nuclear system will show a liquid-gas phase transition. This is based on two well-known facts, namely, (i) the similarity of the nucleon-nucleon interaction with its general feature of repulsion followed by attraction with the Van der Waals forces, and (ii) the overwhelming success of the liquid drop model. The earliest search in this regard has been in the high-energy proton induced Xe and Kr reaction using the prescription of Fisher droplet model [1]. The successful description of the mass yield characterized by the power law distribution, through such a model was considered indicative of the signature of a liquid-gas phase transition. However, many other models without having explicitly the mechanism of a liquid-gas phase transition in them [2–5], could also explain the data. This has dampened the interest of the community about this interesting possible phenomenon. However, in the last couple of years there has been renewed interest due to more extensive experimental investigation [6,7] to find critical exponents in the multifragmentation of Au nuclei. A desirable feature of any experimental detection of a phenomenon should be the measurement of such observables whose interpretation would require a minimal amount of theory or model. This would lead to ''theory independence'' of the conclusions. In the present context, a more appropriate attempt would be to measure the excitation energy and temperature of hot nuclear systems. The caloric curve thus obtained, should show the well-known feature of a liquid-gas phase transition in a more definitive term. Such an attempt by Pochodzalla *et al.* through their study on Au+Au reaction and analysis of other reactions [8] shows a behavior with characteristics of a phase transition. Defining the temperature in terms of the yields of He and Li, they find the temperature remains constant at about 5 MeV for the entire range of excitation energy 3 to 10 MeV/nucleon. For higher-excitation energy, the temperature increases monotonically. This has once again brought the topic of a liquid-gas phase transition in a nuclear system to the frontier of heavy-ion physics. This situation warrants theoretical study to see if it is possible to obtain a realistic caloric curve using known features of nuclear dynamics.

In the past, many theoretical attempts have been made to study the thermostatic properties of hot nuclear matter using a nucleon-nucleon interaction in the framework of Thomas-Fermi models [9–11] and temperature dependent Hartree-Fock [12,13] models. Using the equation of state so obtained, critical temperatures in the range 15 to 20 MeV for a liquid-gas phase transition in infinite nuclear matter have been found. It must be emphasized here that such calculations deal with a process in which nuclear liquid goes into nucleonic gas. This gas is supposed to have only pure nucleons without any clusters. However, in the realistic situation, besides the nucleons, many fragments of varying mass number will also be produced. Hence in the theoretical calculation of a caloric curve, the emission of heavy-mass fragments need to be taken into account. A possible way for reliable calculation may be through the statistical multifragmentation model, where the production of such fragments together with pure nucleons can be conveniently considered. However the key question is how reliably one can calculate the excitation energy dumped into the system and the consequent rise in temperature. When some energy is imparted to a nucleus, there are several modes through which the nucleus will receive the energy. The part of the energy which goes to the compression or collective modes will not contribute to the rising of temperature of the system. Further the precise relation between the bombarding energy and the excitation energy must be known in order to make contact with the experiments in the laboratory. The identification of the true mechanism of energy deposition and consequent rise of temperature depends upon the nucleon-nucleon collisions at a microscopic level, which requires undoubtedly the solution of an extremely involved many-body problem. Therefore a mechanism is invariably supposed for the calculation, which has to be *a posteriori* justified through experimental support.

Recently we have developed a model, called the dynamic statistical multifragmentation (DSM) model [14,15], for the intermediate energy heavy-ion collisions, where the entrance channel characteristics like incident energy, impact parameter, and masses of colliding nuclei are taken into account. The model is based on a spectator-participant picture and envisages the tripartition of the whole system into the fireball, the projectilelike and targetlike spectators. Well-defined mechanisms for the excitation of the three parts are clearly recognizable in this model. The excitation of the spectator parts originates from the distortion of their shapes and that of the fireball due to the fusion of the participant regions of the

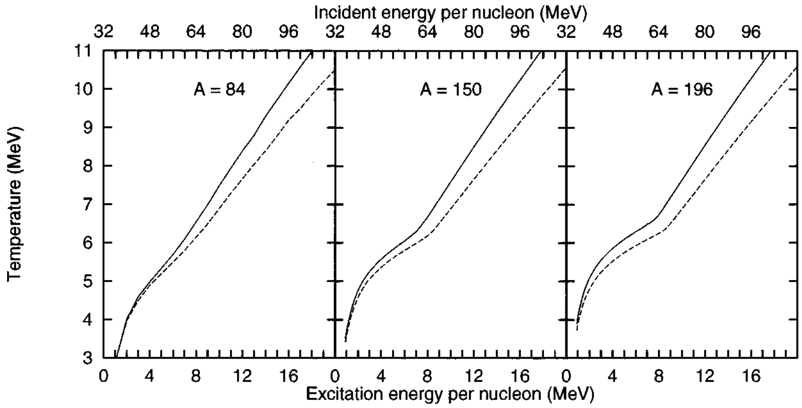

FIG. 1. Caloric curve for the fireball with $A=84$, 150, and 196. The solid and dashed lines are for densities $0.22\rho_0$ and $0.115\rho_0$, respectively.

two colliding nuclei. So the excitation energy of the fireball could be calculated using relativistic kinematics and that of the spectators from the geometrical considerations. Then the decay of the three systems are calculated in the framework of statistical mechanics using a grand canonical picture. This model explains well the central collision data of ^{40}Ar induced ^{45}Sc reactions [16], and also the noncentral collision data of ^{40}Ar induced ^{40}Ca and ^{197}Au reactions [17], with incident energies in the intermediate range of 30 to 140 MeV/nucleon. This success gives us the impetus to calculate the caloric curve in the DSM model, for reactions which we feel will correspond to the realistic situation and can be compared with experimental observations.

In the present work, we report our calculation of a caloric curve in the ^{197}Au+^{197}Au reaction obtained by varying the incident energy from 35 to 130 MeV/nucleon. Our notations are similar to Refs. [14,15]. The spectators, being severed from the target and projectile nuclei are relatively cold, and not amenable for the adequate deposition of energy from the projectile. So it is the fireball only, in which different amounts of energy can be deposited by varying the incident energy. Further, experimentally this part can be isolated kinematically from the spectators ones and its decay can be studied. So the fireball offers a convenient system to obtain the caloric curve and study its features. For a given impact parameter we can find [14,15] the number of constituting nucleons in the fireball from the geometry of the collision and the excitation energy E^* from the incident energy, $E_{\rm lab}$. For different impact parameters we can have fireballs having different mass (A) and charge (Z) numbers. Then we consider the decay of the fireball into all possible fragments of varying mass and charge numbers detected by the available phase space in various channels. The temperature of the fireball is determined by simultaneously solving the baryon number, charge number, and energy conservation equations, as given in Ref. [15]. We would like to stress here that, in our calculation we have taken both the interfragment Coulomb and nuclear interactions together into account through a statistical prescription [14,15,18–20],

In the DSM model, the freeze-out density of the fireball is the only parameter. Here we have performed our calculation with two different densities, namely $0.22\rho_0$ and $0.115\rho_0$, ρ_0 being the density of nuclear matter at ground state. In Fig. 1, we have plotted the caloric curve for the ^{197}Au+^{197}Au collision at three different impact parameters, 5.8, 6.95, and 8.8 fm, which correspond to fireballs of mass and charge numbers (84, 32), (150, 60), and (196, 78), respectively. The upper scale shows the incident energy of the projectile. In the figure, the solid and dashed lines represent the caloric curve obtained with two freeze-out densities $0.22\rho_0$ and $0.115\rho_0$, respectively. We find for the two heavier systems, the temperature rises faster for a very low-excitation energy, up to $\sim$3 MeV/nucleon, and then the rise is slower. Between 3 to 8 MeV/nucleon excitation energy, the temperature remains rather constant at 5 to 6 MeV in these cases. A kink is seen in each of the four curves at an excitation energy of about $\sim$8 MeV/nucleon. Depending on the mass and the freeze-out density, the corresponding temperatures lie within $\sim$6 to 6.5 MeV. Then with the increase in incident energy, the temperature rises monotonically. This is comparable with the experimental finding of Pochodzalla *et al.* [8], where they observe the temperature to remain constant at 5 MeV when the excitation energy increases from 3 to 10 MeV/nucleon, and a kink is seen at 10 MeV/nucleon. Remarkably, they characterize the density where this phenomenon is observed, to be in the range $0.15\rho_0$ to $0.3\rho_0$ which includes the density $0.22\rho_0$ used in the present calculation. It may be noted that, in our calculation, this kink is missing in the case of a lighter mass system $A=84$. This suggests that in the lighter systems, this phenomenon is not likely to be manifested. We calculated the caloric curve for a series of systems with varying mass numbers and found that the constancy of temperature over a certain range of excitation energy, the kink in the caloric curve starts showing up only when the number of nucleons in the system is more than $\sim$120, which is in agreement with Gross [21]. However, Bondrof *et al.* [22] gets such behavior even for a low mass system $A=100$. De *et al.* have also attempted to calculate the caloric curve for a ^{150}Sm nucleus in the Thomas-Fermi model [23]. However, they find a kink at a much higher-excitation energy of about $\sim$18 MeV/nucleon with a corresponding temperature $T\sim10$ MeV for the density $0.125\rho_0$. They do not find such behavior for higher densities.

To see what effect the nature of interfragment interaction has on this result, we have calculated these caloric curves with switching on and off the nuclear interaction which is normally not taken into account in many calculations [21,22]. In Fig. 2, we have presented the caloric curves obtained with interfragment Coulomb plus nuclear interaction and Coulomb interaction only by solid and dashed lines, respectively, for the density $0.22\rho_0$. We find, when the nuclear

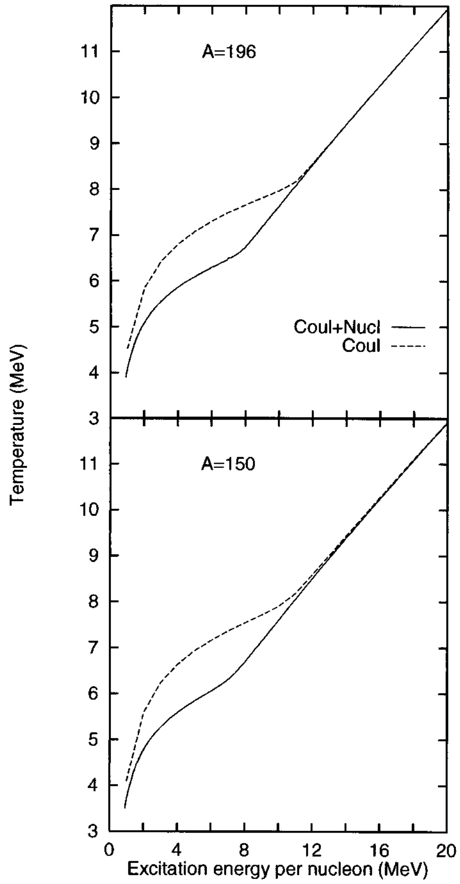

FIG. 2. Caloric curve for the fireball with $A=150$ and 196. The solid and dashed lines are the calculation with Coulomb plus nuclear and only Coulomb interfragment interaction, respectively.

interaction is switched off, the kink gets shifted to a higher value of excitation energy of 12 MeV/nucleon with a temperature of ~8 MeV. This takes us substantially away from the experimental result. The coming down of the temperature of the fireball to the realistic value when nuclear interaction is included is in accord with our earlier studies. Such lowering is expected as the nuclear interaction being attractive in nature, tends to reduce the kinetic energy of the fragments in the assembly and consequently the temperature. Gross in his model study of decay of hot nuclei [21] in the framework of microcanonical formalism, finds the temperature to remain constant for a very short range of excitation energy. This may be because he does not take the nuclear interfragment interaction into account and also treats the neutron channel separately. However, in the present study using the DSM model, all the channels are treated on an equal footing due to the inclusion of interfragment nuclear interactions. This leads to a more realistic caloric curve with the appropriate value of excitation energy and temperature comparable with the experiment.

With a view to see whether the kink found in the caloric curve is related to a phase transition, we have calculated the specific heat of the system from the caloric curve. It is the relevant observable of the system, defined as

$$C_v=(dE^*/dT)_v . \quad (1)$$

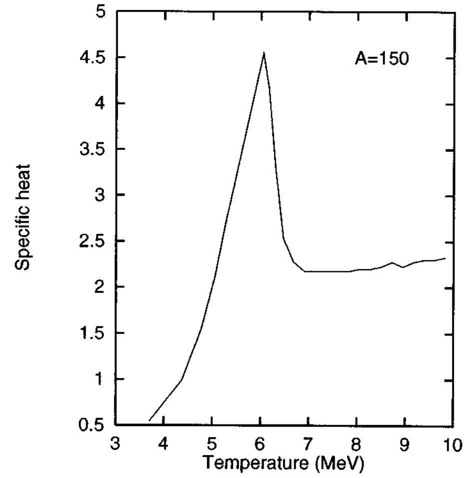

FIG. 3. Specific heat distribution for fireball with $A=150$.

In Figs. 3 and 4 we have plotted the calculated C_v versus the temperature for the density $0.22\rho_0$, the fireballs of masses $A=150$ and 196, respectively. We find a well-defined peaked structure signaling the possible existence of a liquid-gas phase transition at $T\sim6$ MeV for $A=150$ and $T\sim6.5$ MeV for $A=196$. This transition is expected in the nuclear system with the excitation energy in the range 8 to 10 MeV/nucleon.

In summary, we have obtained the caloric curve for the system $A=84$, 150, and 196, likely to be produced in ^{197}Au+^{197}Au collision. It is found that the mechanism of energy deposition through the tripartition picture of the DSM model and the interfragment nuclear interaction play the decisive role in producing a realistic caloric curve. The temperature is shown to remain nearly constant at 5 to 6 MeV for the range of excitation energy 3 to 8 MeV/nucleon, which is close to experimental observation. We find such behavior is only seen when the mass of the system is more than ~120. A kink is seen at an excitation energy of 8 MeV/nucleon, corresponding to a temperature of ~6 to 6.5 MeV, which is speculated to be related to a liquid-gas phase transition. This

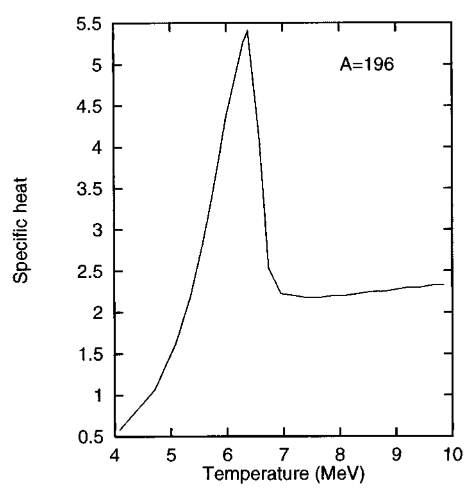

FIG. 4. Same as Fig. 3, but for $A=196$.

possible signature of phase transition is more clear from the specific heat distribution which shows a peak structure at this temperature. Hence this temperature may be treated as a critical temperature of a liquid-gas phase transition in finite nuclear matter. However, the determination of the order of this transition and finding out proper critical exponents are quite important factors for establishing this liquid-gas phase transition.

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