Dynamical study of spinodal decomposition in heavy ion collisions

A. Barrañón *; J. A. López[†]

Nov, 2^{nd} , 2004

Abstract

Nuclei undergo a phase transition in nuclear reactions according to a caloric curve determined by the amount of entropy. Here, the generation of entropy is studied in relation to the size of the nuclear system.

1 Introduction

Collisions at hundreds of MeVs break the nuclei into several fragments[1]. This fragmentation led to the determination[2, 3] of the relation between the system's temperature and its excitation energy, *i.e.* the caloric curve, CC. A striking feature of the CC is the dependence of the transition temperature, *i.e.* the "plateau" temperature T_p , with the mass of the breaking system. Recent observations[4] show that lighter systems, *i.e.* with masses between 30 to 60 nucleons have a $T_p \approx 9 \ Mev$, while systems with masses between 180 to 240 yield a $T_p \approx 6 \ MeV$. This variation of T_p has been linked to the entropy generated during the reaction[5, 6]. Here these collisions are used to find the relationship between the entropy generated in the reaction and the size of the fragmenting system.

2 Caloric curve and entropy

Ions fuse in collisions and reach some maximum density and temperature, to then expand cooling and reducing the density[7, 8]. In the densitytemperature plane[9], this corresponds to a displacement from normal saturation density and zero temperature, $(n_o \approx 0.15 \ fm^{-3}, T = 0)$, to some higher values of (n, T), to then approach $n \to 0$ and $T \to 0$ asymptotically.

These reactions include phase changes and non-equilibrium dynamics, and are best studied with molecular dynamics. The model we use is "LATINO"[10], combined with the fragment-recognition code ECRA[11];

^{*}Universidad Autónoma Metropolitana. Unidad Azcapotzalco. Av. San Pablo 124, Col. Reynosa-Tamaulipas, Mexico City. email: bca@correo.azc.uam.mx

[†]Dept. of Physics, The University of Texas at El Paso. El Paso, TX, 79968

these, without adjustable parameters, have described reactions [12], phase transitions [13], criticality [14], and the CC[5, 6].

The right panel of figure 1 shows trajectories in the n-T plane of collisions simulated with "Latino" and corresponding to central collisions of Ni + Ni at energies between 800 to 1600 MeV. As during the reaction, nucleons evaporate leaving a smaller system, the trajectories follow different paths on the plane according to the residual size of the nuclear system. The plot shows the cases of systems with 49, 75, and 91 nucleons.

As noted before [5, 6], these trajectories are determined by the entropy generated in the beginning of the reaction. These reactions can help to relate the caloric curves to system size, and to the amount of entropy generated.

2.1 Mass dependence of the caloric curve

Central collisions were performed for Ni + Ag at different beam energies. During the collision, n and T of the 50% most central particles were determined as a function of time. At the same time, ECRA was used to identify the fragment source size, fragmentation times, fragment stability, and other quantities of interest. This information was then used to obtain the caloric curve as a function of the source size.

The left panel of figure 2 shows caloric curves obtained by *Latino* in central collisions of Ni + Ag at energies between 1000 to 3800 MeV. The three groups correspond to different masses: circles for collisions with residual sources of 40 to 59 nucleons, rectangles for 60 to 79, and crosses for 80 to 100 nucleons. The symbol sizes denote the standard deviations of T and excitation energy of each energy bin. The lines, average values of T of the last few points of each mass range, clearly show the inverse relationship between the transition temperature, T_p , and source size, as observed experimentally[4].

2.2 Entropy dependence of the caloric curve

The collision takes a T = 0 quantum-system to a hot and dense "quasiclassical" state through a non-equilibrium path, which then expands and decomposes spinodaly. In terms of entropy, the system goes from an initial S = 0 state to a high-entropy state, to then coast into an isentropic expansion until a violent spinodal decomposition increases entropy again.

Latino + ECRA allow the evaluation of the entropy during the reaction. Neglecting quantum effects, the entropy per particle S can be quantified in units of Boltzmann's constant as for a classical gas[16] through $S = \log \left[\frac{1}{n} \left(\frac{3T}{2}\right)^{3/2}\right] + S_o$, where S_o depends on the nucleon mass[5].

Figure 2 shows the entropy of central collisions of Ni + Ni at energies between 600 to 2000 MeV plotted against the size of the residual fragmenting source. The bottom curve corresponds to the entropy achieved at maximum heating and compression, *i.e.* the value at which the system expands until it decomposes; the one responsible for determining T_p . The top curve, on the other hand, is the asymptotic value of S, and it includes all other increases of entropy that took during the phase change and expansion. Both of these curves show that lighter systems are more apt to generate entropy, and that the phase change and final expansion succeed in increasing the initial entropy.

3 Conclusions

These results confirm previous results [5, 6], the initial stage of the reaction reaches a value of S which defines the trajectory of the compound nucleus into a spinodal decomposition. The transition temperature T_p is thus defined by the intersection of the isentrope and the spinodal. The present study further confirms that the amount of entropy generated initially in the reaction varies inversely with the size of the fragmenting system. This inverse relationship is also maintained after the phase change. Unfortunately, as concluded in previous studies, the observed relationship between S and source size was obtained with *LATINO*, and does not explain what causes lighter systems to generate more entropy than heavier ones in heavy ion collisions. We propose to continue with this study in the near future.

References

- [1] P. F. Mastinu et al., Phys. Rev. Lett. B76, 2646 (1996).
- [2] J. Pochodzalla et al., Prog. Part. Nucl. Phys 39, 43 (1997).
- [3] H. Feldmeier et al., Gross properties of nuclei and nuclear excitations, GSI, Darmstadt, (1999).
- [4] J. B. Natowitz et al., Phys. Rev. C65, 034618 (2002).
- [5] A. Barrañón, J. Escamilla, and J. A. López, *Phys. Rev.* C69, 014601 (2004).
- [6] A. Barrañón, J. Escamilla and J. A. López, Bras. J. Phys., 34, 904 (2004).
- [7] G. F. Bertsch, and P. Siemens, Phys. Lett. B126, 9 (1983).
- [8] J. A. López and P. Siemens, Nucl. Phys. A314, 465 (1984).
- [9] J. A. López and C. O. Dorso, Lecture Notes on Phase Transitions in Nuclear Matter, World Scientific, Singapore, (2000).
- [10] A. Barrañón et al., Rev. Mex. Fís. 45-Sup.2, 110 (1999).
- [11] A. Strachan and C. O. Dorso, Phys. Rev. C56, 995 (1997).
- [12] A. Chernomoretz et al., Phys. Rev. C65, 054613 (2002).
- [13] A. Barrañón, C. O. Dorso and J. A. López, R. Mex. Fís. 47-Sup.2, 93 (2001).
- [14] A. Barrañón et al., Heavy Ion Phys. 17-1, 59 (2003).
- [15] A. Barrañón, C. O. Dorso and J. A. López, Infor. Tecnológica 14, 31 (2003).
- [16] K. Huang, Stat. Mech., 2nd edition, John Wiley & Sons, New York, (1987).

This figure "fig1.jpg" is available in "jpg" format from:

http://arxiv.org/ps/nucl-th/0503077

This figure "fig2.jpg" is available in "jpg" format from:

http://arxiv.org/ps/nucl-th/0503077