Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics A 791 (2007) 222–231
NUCLEAR PHYSICS A

Time dependence of isotopic temperatures

Armando Barrañón [a], Claudio O. Dorso [b], Jorge A. López [c,*]

[a] *Universidad Autónoma Metropolitana–Azcapotzalco, México D.F., Mexico*
[b] *Universidad de Buenos Aires, Nuñez, Argentina*
[c] *University of Texas at El Paso, El Paso, TX 79968, USA*

Received 4 October 2006; received in revised form 22 March 2007; accepted 12 April 2007

Available online 20 April 2007

This work is dedicated to the memory of Vijay R. Pandharipande

Abstract

In this study the double isotope yield ratio thermometer, commonly used in heavy ion reactions, is put to the test in molecular dynamics simulations for a variety of nuclear reactions and energies. Comparing results to other estimates of the temperature and to experimental measurements, it is determined that the double isotope yield temperature indeed reflects the hot and dense phase of the reaction. Correlations between the double isotope yield temperature, the system size, beam energies, and collision times were investigated.

Keywords: Heavy ion collisions; Nuclear fragmentation

1. Introduction

A precise determination of the temperature achieved in nuclear reactions has become a priority in the study of heavy ion reactions. For example, recent investigations involving radioactive isotopes [1–5] promise to elucidate the role of the asymmetry mass terms of the nuclear equation of state through the phenomenon of isoscaling. For this, however, similar but isotopically different reactions must reach a common equilibrium temperature T at the same time. As the resolution needed to determine this *thermal symmetry* between different reactions is very high, a study of the time evolution of the reaction's temperature is clearly in order.

* Corresponding author.
E-mail address: jorgelopez@utep.edu (J.A. López).

0375-9474/$ – see front matter
doi:10.1016/j.nuclphysa.2007.04.008

A recent study of such time dependence was performed using the kinetic energy variation of emitted light clusters [6]. Based on results from theoretical models [7,8] and experiments [9,10] that show a correlation between the emission time and the energy of early emitted particles, the study uses the *AMD-V* model [8] to calibrate the emission time scales and follow the time evolution of the system. Although this analysis illuminates interesting features of the kinetics of the reaction, we believe it has to be confirmed by an independent approach.

Thus the motivation of the present study: to understand what one of the most commonly used indicators of temperature, the double isotope yield ratio thermometer, measures in a heavy ion reaction. This will be done using a molecular dynamics code, *Latino*, which will simulate the experimental reactions using the same combination of nuclei and beam energies as the experimental study.

The structure of the article is as follows: in the next section the different measures of the temperature to be used will be briefly introduced and connected to molecular dynamics. Then, these measures will be used in Section 3 in two different situations: to a study case, in Section 3.1, in which the production of the different species is carefully dissected for the full understanding of the thermometers; and, in Section 3.2, to a variety of reactions and beam energies for comparison to experimental data. The paper will close with some conclusions in Section 4.

2. Measuring temperature in heavy ion reactions

As the temperature of a nuclear reaction cannot be uniquely defined, it is best to describe the reaction with a plausible scenario. Basic arguments [11,12] suggest that collisions can fuse the participating nuclei, initially at normal density, zero temperature, and zero entropy, into a compound nucleus that reaches a maximum density, temperature and entropy, which then bounces into an expansion that drives the system into the fragmentation [13,14]. Under this scenario, it is clear that temperature can only be defined in a conditional manner.

2.1. Measuring the temperature in molecular dynamics

As heavy ion reactions take nuclei from equilibrium to a hot and dense phase, and then to an expanding and disassembling state, its study requires a model capable of reproducing the collision dynamics including stages in- and out-of-thermal equilibrium. As statistical and other equilibrium and dynamical models [15–21] lack—by construction—of all relevant collision-induced correlations or of all higher-order correlations needed to produce appropriate fragmentation, in this study we use a molecular dynamics (MD) model that can describe non-equilibrium dynamics and changes of phase without adjustable parameters.

The model "*Latino*" [22], which uses the Pandharipande potential (Coulomb plus a two-body nuclear [23]) and a fragment-recognition algorithm [24], reproduces nucleon–nucleon cross sections, the correct binding energies and densities of real nuclei. In the recent past it has been used to study neck fragmentation [13], phase transitions [25], critical phenomena [26,27], the caloric curve [14,28], and—most recently—isoscaling [29] in nuclear reactions.

With this model one can obtain an approximate view of the thermalization process [30]. After the biggest fragment is identified during a collision (through *ECRA* [24], *MSTE* or another method), its temperature can be calculated from the nucleon's kinetic energies $\{K_i\}$ (with respect to the center of mass of the moving fragment) through $T_{\mathrm{BF}} = \sum_i 2K_i/3N$. Tracking the fragment during the collision can help us determine T_{BF} as a function of time.