Comparison between nuclear thermometers in central Xe+Sn collision (Postprint)

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Date: 2023-06-18T00:00:00+00:00

Abstract

The temperature of the fragmenting source in central heavy-ion collisions at Fermi energies is investigated using the isospin-dependent quantum molecular dynamics model combined with the statistical decay model GEMINI. Five distinct nuclear thermometers are employed to extract the nuclear temperature. We find that the He and Li isotope temperatures reach a plateau at beam energies of approximately 70–100 MeV/nucleon. The slope temperature and quadrupole fluctuation temperature yield high values. The quantum slope temperature and quantum quadrupole fluctuation temperature are closer to the He and Li isotope temperatures.

Full Text

Preamble

Comparison between Nuclear Thermometers in Central Xe+Sn Collisions

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Abstract

The temperature of fragmenting sources in central heavy-ion collisions at Fermi energies is investigated using the isospin-dependent quantum molecular dynamics model in combination with the statistical decay model GEMINI. Five different nuclear thermometers are employed to extract the nuclear temperature.

We find that the He and Li isotope temperature reaches a plateau at beam energies of about 70–100 MeV/nucleon. The slope temperature and quadrupole fluctuation temperature yield high values, while the quantum slope temperature and quantum quadrupole fluctuation temperature are closer to the He and Li isotope temperatures.

Keywords
Heavy-ion collision, Nuclear temperature, Phase transitions

Introduction

Nuclear matter may undergo a phase transition from the liquid ground state to a gas of nucleons when heated. The nature of the interaction between nucleons is similar to Van der Waals forces between molecules. Uncertainties in the nuclear equation of state (EOS) make the study of the nuclear liquid-gas phase transition important and meaningful [**?**, **?**]. Experimental signals of phase transitions have been observed by many experimental groups [**?**], and significant theoretical efforts to identify signatures of phase transitions in heavy-ion collisions (HICs) have been undertaken in recent years [**?**]. HICs at intermediate energies offer an opportunity to heat nuclei, and nuclear multifragmentation has long been associated with the nuclear liquid-gas phase transition.

Temperature is one of the most important degrees of freedom for describing phase transitions. However, the nuclear matter created in HICs is a non-equilibrium, finite, and open system, making temperature determination more difficult than in ordinary matter. Consequently, nuclear thermometers are more complicated than conventional thermometers. Several nuclear thermometers have been proposed in the past, which can be divided into three families [**?**, **?**]:

(1) **Kinetic approaches**. These are based on the assumption that the kinetic energy spectra of particles obey a Maxwell-Boltzmann distribution. Temperature can be derived from the kinetic energy spectra [**?**, **?**] or from momentum fluctuations [**?**]. It has been suggested that the slopes of light product spectra in nuclear reactions lead to very high "temperatures." The temperatures extracted from the Maxwell-Boltzmann kinetic approach likely reflect not only the thermal properties of the system but also collective energies arising from the dynamics of the nuclear collision. Recently, the Fermi-Dirac kinetic approach has been considered to improve this type of thermometer [**?**, **?**].

(2) **Population approaches**. The underlying idea for this method is that the relative populations of produced clusters or their excited states are assumed to obey a Boltzmann distribution. Population of excited states [**?**] and double ratios of isotopic yields [**?**] are two of the most frequently used methods. Using the isotopic thermometer, Pochodzalla et al. obtained the caloric curve that is taken as evidence for the occurrence of a liquid-gas type phase transition [**?**]. An example is the isospin thermometer, which varies with the neutron-to-proton ratio N/Z [**?**].

(3) **Thermal-energy approaches**. The temperatures at freeze-out are obtained from the excitation energy, which is extracted by measuring evaporation cascades from a thermalized source.

In this paper, we compare five different nuclear thermometers. Central collisions of ^{129}Xe+^{120}Sn at Fermi energies are simulated using the isospin-dependent quantum molecular dynamics (IQMD) model together with the statistical decay code GEMINI. The double ratio temperature, slope temperature, quantum slope temperature, quadrupole fluctuation temperature, and quantum quadrupole fluctuation temperature are compared.

Supported by National Natural Science Foundation of China (Grant Nos. 11025524 and 11161130520) and National Basic Research Program of China (Grant No. 2010CB832903).
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Received date: 2013-06-27

IQMD Transport Model

The IQMD model [**?**, **?**] is based on the same principles as the quantum molecular dynamics model. With consideration of different mean-field potentials for protons and neutrons, and the production of pions and kaons, the IQMD model has been widely and successfully used for analyzing collective flows, stopping, and pion and kaon multiplicities in HICs at energies below 2 GeV/nucleon [**?**]. The statistical code GEMINI was proposed by R. J. Charity in the 1980s [**?**]. It can be utilized to treat the decay of a compound nucleus in fusion reactions and excited fragments in HICs. The GEMINI code has frequently been applied to transport models to statistically deexcite hot fragments [**?**]. Recently, within the framework of the IQMD+GEMINI model, the odd-even effect in fragment yields has been well reproduced [**?**]. Using the same model, we have investigated multiplicities and kinetic energy spectra in central HICs, finding that the simulations are in very good agreement with experimental data. The slope temperature and isotope temperature were also studied [**?**, **?**]. The transport model with modified nucleon-nucleon elastic cross-section (the medium factor) and soft EOS [**?**, **?**] are used to study the nuclear temperature. To compensate for the fermionic phase-space density feature, the constraint applied in the constrained molecular dynamics model [**?**] is utilized.

[Figure 1: see original paper]

3.1 He and Li Isotope Temperature

Figure 1 [Figure 1: see original paper] displays the charge distribution of fragments produced in central collisions of ^{129}Xe+^{120}Sn at 50 MeV/nucleon (impact parameter $b < 1.6$ fm). Both simulations by IQMD with and without the GEMINI code are shown in the figure, along with experimental data represented by symbols. Firstly, it is clear that IQMD+GEMINI reproduces the experimental data quite well. Secondly, with the help of the GEMINI code, the yield of heavier fragments decreases and that of light particles increases due to deexcitation of hot fragments. This good agreement with experimental data makes the study of the double ratio temperature possible and reliable.

We introduce one double ratio temperature that uses He and Li isotopes, denoted as T_{HeLi}. It is defined by

$$T_{HeLi} = \frac{13.3\ \text{MeV}}{\ln\left(2.2 \times \frac{Y(^6\text{He})/Y(^4\text{He})}{Y(^7\text{Li})/Y(^6\text{Li})}\right)}$$

where Y is the yield of the isotope. The temperature T_{HeLi} can be calculated using this formula.

3.2 The Slope and Quantum Slope Temperature

Figure 2 [Figure 2: see original paper] illustrates the calculated (open circles) and experimental (open stars) kinetic energy spectra of free protons produced in central collisions of ^{129}Xe+^{120}Sn at $E_{lab} = 50$ MeV/nucleon. The solid lines in each panel denote Maxwell-Boltzmann fits expressed as

$$\frac{dN}{dE} \propto \sqrt{E} \exp\left(-\frac{E}{T_{slope}}\right)$$

where E_0 reflects the repulsive Coulomb forces [**?**].

Taking into account the Fermi nature of nucleons, the slope temperature was rewritten by Bauer [**?**] as

$$T'_{slope} = T_{slope} \times \frac{1}{1 + \frac{E_F}{T_{slope}}}$$

where E_F is the Fermi energy. T'_{slope} is named the quantum slope temperature.

[Figure 2: see original paper]

3.3 Quadrupole Fluctuation and Quantum Quadrupole Fluctuation Temperature

A new nuclear thermometer based on momentum fluctuations of detected particles was proposed in Ref. [**?**]. The momenta of particles were assumed to obey the Maxwell-Boltzmann distribution, giving

$$\sigma_{xy}^2 = mT_{fluct}$$

where m is the mass of the particle, and p_x, p_y, and p_z are the three momentum components. The variance σ_{xy}^2 can be obtained from the quadrupole distribution through

$$\sigma_{xy}^2 = \int dp\, Q_{xy}(p)$$

Figure 3 [Figure 3: see original paper] shows the quadrupole distribution for free protons, which is similar to experimental results [**?**]. The temperature T_{fluct} can then be extracted from these formulae, with results shown in Fig. 4. More details will be discussed in the following section.

The fluctuation temperature was improved as follows [**?**]:

$$T'_{fluct} = T_{fluct} \times \frac{1}{1 + \frac{E_F}{T_{fluct}}}$$

where E_F is the Fermi energy of nuclear matter. T'_{fluct} is named the quantum quadrupole fluctuation temperature.

[Figure 3: see original paper]

3.4 Comparison between Nuclear Thermometers

Within the IQMD+GEMINI model, we calculated central ^{129}Xe+^{120}Sn collisions at incident energies from 30 MeV/nucleon to 100 MeV/nucleon. Five nuclear thermometers are investigated in this work: the double ratio temperature T_{HeLi}, the slope temperature T_{slope}, the quantum slope temperature T'_{slope}, the quadrupole fluctuation temperature T_{fluct}, and the quantum quadrupole fluctuation temperature T'_{fluct}. The results are shown in Fig. 4.

Firstly, different thermometers give very different values of nuclear temperature. The discrepancy between various temperatures steadily grows with increasing incident energy. All temperatures exhibit an increase in value with increasing incident energy, but the He and Li isotope temperature reaches a plateau at about 70–100 MeV/nucleon of beam energy.

Secondly, T_{slope} and T_{fluct} are very close to each other because both approaches assume a Maxwell-Boltzmann type momentum distribution (Eq. (2)). These two temperatures are the highest of all because, besides thermal motion, they also contain Fermi motion.

Thirdly, T'_{slope} and T'_{fluct} are both smaller than T_{slope} and T_{fluct} because the Fermi motion of nucleons is removed. However, due to different methods of eliminating the Fermi motion, the results differ. Both T'_{slope} and T'_{fluct} are more consistent with T_{HeLi}.

[Figure 4: see original paper]

4 Conclusion

Within the IQMD+GEMINI model, various nuclear thermometers have been investigated for central collisions of ^{129}Xe+^{120}Sn at incident energies ranging from 30 to 100 MeV/nucleon. These nuclear thermometers do not exactly coincide with each other. The He and Li isotope temperature reaches a plateau at about 70–100 MeV/nucleon of beam energy. The slope temperature and quadrupole fluctuation temperature give higher values than others because the Fermi motions of nucleons are not eliminated. The quantum slope temperature and quantum quadrupole fluctuation temperature are closer to the He and Li isotope temperature because the Fermi motion is removed.

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