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Temperature and density of hot decaying ^{40}Ca and ^{28}Si

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Summary. — By means of quantum-fluctuation analysis techniques, temperatures and local partial densities of bosonic and fermionic fragments produced in the decay of hot ^{40}Ca and ^{28}Si projectile-like sources produced in mid-peripheral collisions at sub-Fermi energies have been obtained. The used method treats bosonic and fermionic fragments differently. The purpose of such treatment is to trace important quantum effects such as fermion quenching or Bose-Einstein Condensation (BEC) in nuclei.

1. – Introduction

A nucleus is a quantum many-body system made of strongly interacting fermions, protons and neutrons (nucleons). This produces a rich Nuclear Equation of State (NEOS) which is usually a function of density and temperature and whose knowledge is crucial to our understanding of the composition and evolution of celestial objects [1]. In heavy-ion collisions, highly excited systems may be formed and, under some conditions, a temperature and a density may be recovered from experimental observations or models. In this way it is possible to investigate the NEOS at finite temperature. In the Cyclotron Institute at Texas A&M University we have run the experiments with heavy-ion collisions using the NIMROD array. Our experiments employed 10, 25, 35 MeV/*u* beams of ^{40}Ca and ^{28}Si incident on ^{40}Ca , ^{28}Si and ^{12}C . In this paper, the preliminary results of extracted temperatures and densities of decaying hot ^{40}Ca and ^{28}Si in $^{40}\text{Ca} + ^{40}\text{Ca}$ and $^{28}\text{Si} + ^{12}\text{C}$ reactions at 35 MeV/*A* will be presented.

2. – Event selection

The events suitable for this analysis must fulfil certain conditions. We need to select equilibrated source, thus to eliminate particles emitted before the equilibrium is reached. Moreover, we need events with fragments that have α -like (α , ^{12}C , ^{16}O) or d-like structure (d, ^6Li , ^{10}B). Our recent study of the α -like neck structures in the collisions of 35 MeV/nucleon ^{40}Ca with ^{40}Ca [2] revealed that the total equilibration of all degrees of freedom is not achieved in the midperipheral collisions. $Z = 1$ particles and neutrons are primarily pre-equilibrium particles, representing energy dissipation but not energy deposition into the PLF. Moreover, a hierarchy effect is observed in the collision dynamics which significantly increases the difficulty of isolating clean projectile decay samples. For our analysis we have selected the projectile-like sources consisting of only bosons, only fermions, only even-even nuclei, only odd-odd nuclei, only even-odd nuclei and only α -conjugate nuclei, respectively. We employed the total α -like mass (d-like mass) of events consisting of α -conjugate (d-conjugate) nuclei is 40 (for ^{40}Ca decay) or 28 (for ^{28}Si decay) as well as the total mass A_{TOT} of remaining class of events in order

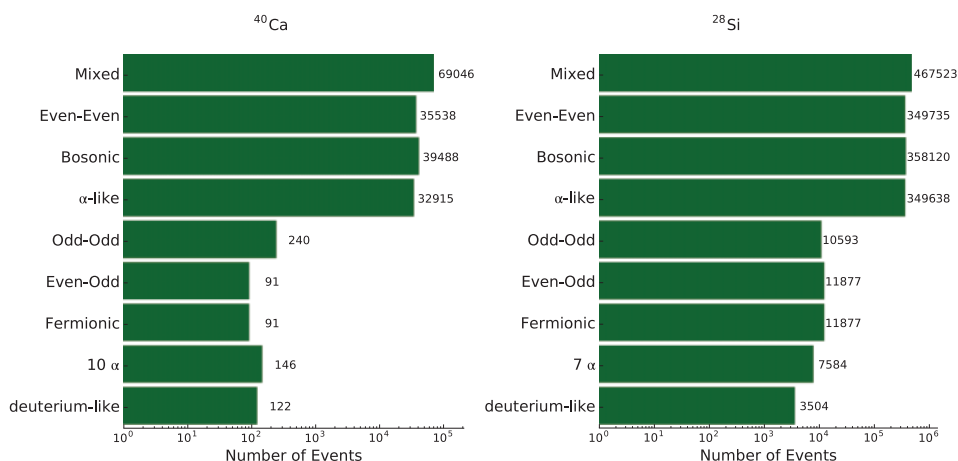


Fig. 1. – The number of events which decayed into a particular type of matter in $^{40}\text{Ca} + ^{40}\text{Ca}$ (left) and in $^{28}\text{Si} + ^{12}\text{C}$ (right).

to select the project-like sources. We have allowed $Z = 1$ particles and neutrons but we have redetermined the excitation energies by excluding the $Z = 1$ particles and neutrons from its calculation. Also α particles with PLF source frame energies greater than 40 MeV were excluded to remove contributions from pre-equilibrium emission or from the target-like source. For a completely equilibrated system, the transverse kinetic energy (times $3/2$) is equal to the total kinetic energy and therefore the ratio R of excitation energy using the transverse kinetic energy on one hand and the total kinetic energy on the other hand, should be close to 1. For the further analysis we have selected events with $0.8 \leq R \leq 1.2$. The number of events which decayed into a particular type of matter in $^{40}\text{Ca} + ^{40}\text{Ca}$ (left) and $^{28}\text{Si} + ^{12}\text{C}$ (right) reaction is shown in fig. 1. The majority of studied classes of matter are events consisting of bosonic fragments, even-even fragments or α -like fragments and the other types of matter are 2 orders of magnitude less likely in ^{40}Ca decay and 1 order less likely in ^{28}Si decay. Therefore further results will be presented only for the most populated types of matter.

3. – Results

The temperatures and mean partial densities of different portions of the colliding systems can be estimated by studying the measured particle quadrupole momentum and multiplicity fluctuations, as well as mean particle multiplicities, according to the method described in [3, 4]. The method takes into account the fermionic and bosonic nature of the particles and their mutual Coulomb repulsion [5]. Figure 2 shows local partial

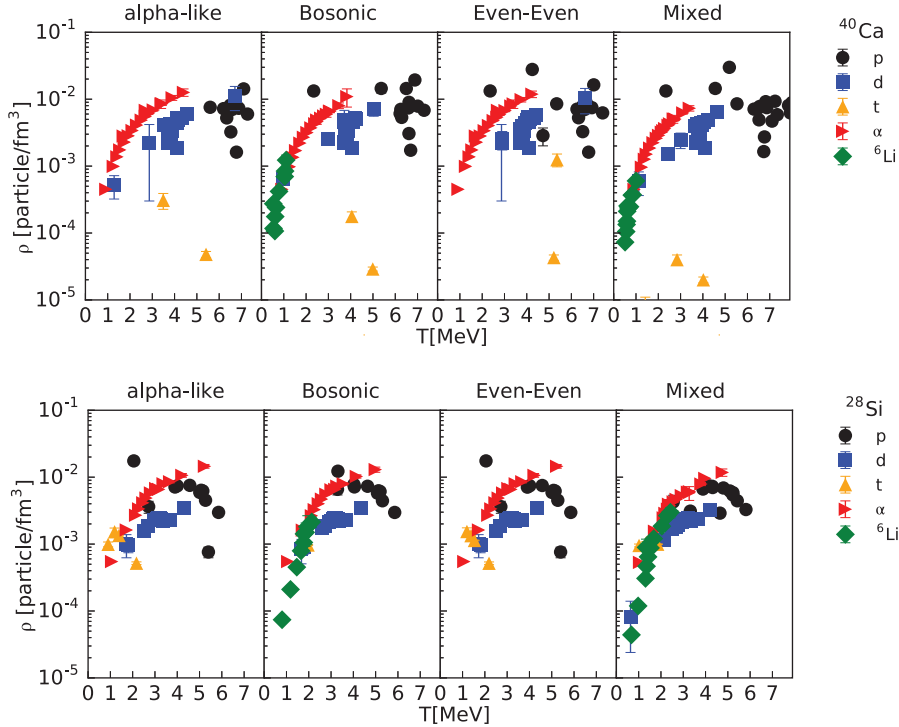


Fig. 2. – Local partial densities *vs.* temperatures probed by bosons (d , α , ^6Li) and by fermions (p , t) for ^{40}Ca (top) and ^{28}Si (bottom) decaying into different types of matter.

densities *vs.* temperatures probed by bosons (d, α , ${}^6\text{Li}$) and by fermions (p, t) for ${}^{40}\text{Ca}$ (top) and ${}^{28}\text{Si}$ (bottom) decaying into different types of matter. As can be seen in the figure, we obtained similar results, regardless of the event selection. It is thus necessary to perform the calculations for other types of matter (fermionic, odd-odd etc.). For ${}^{28}\text{Si}$ decay the statistics is large enough, but for ${}^{40}\text{Ca}$ decay we have only hundreds (or less) of events of different type which makes the results interpretation not trustworthy. We observe different temperatures of the PLF at the emission of each particle and therefore different time scales of the different particle-types emission. Bosons experience rather higher densities than tritons. Protons seem to be emitted from the same region of the nuclei as bosons, which is in contrast to the results obtained by [6] for ${}^{40}\text{Ca}$ decay. This inconsistency needs to be explained. During the process of calculating the temperatures and densities, we have analysed the distributions of particle quadrupole momentum, multiplicity fluctuations and mean particle multiplicities. It is worth to remark, that we have observed multiplicity fluctuations of α -particles larger than 1 for ${}^{28}\text{Si}$ decay into mixed type of matter. That may be a signal of the Bose-Einstein Condensation in nuclei and implies the necessity of performing the calculations above the critical temperature, T_0 , for a condensate [3]. The multiplicity fluctuations larger than 1 have been observed in the excitation energy region, where the Toroid High Spin Isomer (THSI) of ${}^{28}\text{Si}$ has been predicted by Staszczak and Wong [7]. We think we have observed the THSI in ${}^{28}\text{Si}$ decay into 7α [8] but whether these THSIs are the Bose-Einstein condensate need to be confirmed. The analysis is ongoing.

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