EPJ Web of Conferences **117**, 07021 (2016) DOI: 10.1051/epjconf/201611707021
NN2015

Properties of excited A = 40 nuclear systems with varying matter composition

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Abstract

There exists an intriguing problem when bosonic clusters as bound states of fermions are produced in the reaction, and the Bose character of the composite clusters competes with the fermionic properties of their constituents. In the analysis of ^{40}Ca + ^{40}Ca reactions at 35MeV/A we selected classes of projectile-like sources with exit channels consisting of only bosons, only fermions, only even-even nuclei, only odd - odd nuclei, only even - odd nuclei and only alpha-conjugate nuclei, respectively and searched for kinematic characteristics of these systems which might differ depending upon the type of matter selected. The distributions of various observables for the different classes of matter and comparisons between them will be presented and discussed.

1 Introduction

The study of systems composed of mixtures of bosons and fermions stimulates significant theoretical and experimental efforts in different fields of physics. Atomic nuclei are commonly described as systems of strongly interacting fermions, namely neutrons and protons. However, in experiments we observe the existence of phenomena that can be explained by considering nuclei as systems composed of bosonic clusters, the most common being α particles. By considering the nucleus as a mixture of fermions and bosons one may wonder whether the bosonic properties may dominate over the fermionic properties in some instances. Recent theoretical studies indicate, that in heavy ion collisions the produced particles do not follow classical statistics [1] because of the quantum nature, the correct distribution function must be used in the calculations. Protons (p), neutrons (n), tritium (t), etc., follow the Fermi-Dirac statistics [3] [4], while deuterons (d), alphas (α), etc., should follow the Bose-Einstein statistics [5]. In this paper we study the projectile-like sources of different composition and compare the results to the Antissymmetrized Molecular Dynamics Model (AMD) [6] [7] incorporating a statistical decay code GEMINI [8] as a afterburner.

2 Experiment

The experiment was performed in the Cyclotron Institute, Texas A&M University with the multidetector NIMROD-ISiS [9]. The array consists of 14 concentric rings ranging from 3.6^o to 176.0^o in lab. The entire device is housed inside the Texas A&M Neutron Ball, which provides an average neutron multiplicity for each event. Two different detector module configurations were used in the array. The single telescope configuration consisted of a 150μm or 300μm silicon placed in front of the CsI(Tl)-PMT detector. The supertelescope configuration had two silicon detectors, 150μm and 500μm, placed in front of a CsI(Tl)-PMT detector.

3 Event selection

We studied the projectile-like sources consisting of only bosons, only fermions, only even-even nuclei, only odd - odd nuclei, only even - odd nuclei and only alpha-conjugate nuclei respectively. We employed the total α -like mass (d-like mass) of events consisting of α -conjugate (d-conjugate) nuclei

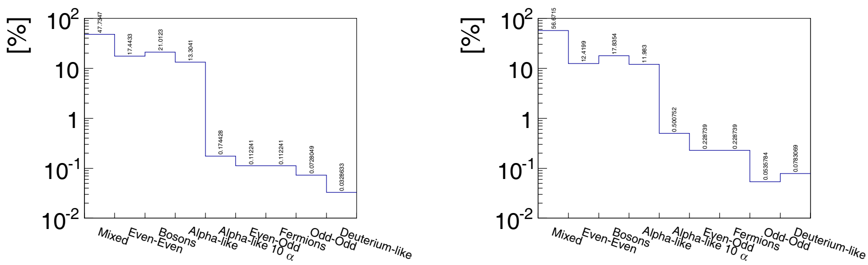

Figure 1: The percentage all events which decayed into a particular type of matter. Left: the experimenta data, right: AMD calculations.

is 40 as well as the total mass A_{TOT} of remaining class of events in order to select the project-like sources. The moving source fit performed on selected class of events indicated, that the light particles (p, d, t) come mainly from the nucleon-nucleon source prior to PLF disassembly and therefore they are not taken into calculations of dynamical variables or PLF excitation energies however they are present in the investigated events. In the Figure 1 the percentage all events which decayed into a particular type of matter is shown, the left panel refers to the experimental data, while the right one to theoretical simulations. It can be seen that almost half of all experimental events are those consisting of Bosons, even-even fragments or α -like fragments and the other types of matter are 2 orders of magnitude less likely. Therefore further results will be presented only for the most populated types of matter. In the AMD calculations the same tendency is also visible, but the difference is not so significant.

4 The number fluctuations

It has been known that fluctuations are large for statistical systems near their critical points, hence the study of multiplicity fluctuations of hadrons produced in high-energy heavy-ion collisions is of importance to study the phase transition [11] [12] [13] [14].

In intermediate energy nuclear collisions the enhancement of multiplicity fluctuations of bosons may be a signal of Bose-Einstein condensation in nuclei [5]. Fermions emitted from a nucleus are subject to the Pauli exclusion principle which may block certain emission channels (Pauli blocking), leading to suppression of the multiplicity fluctuations. In the Figure 2 the

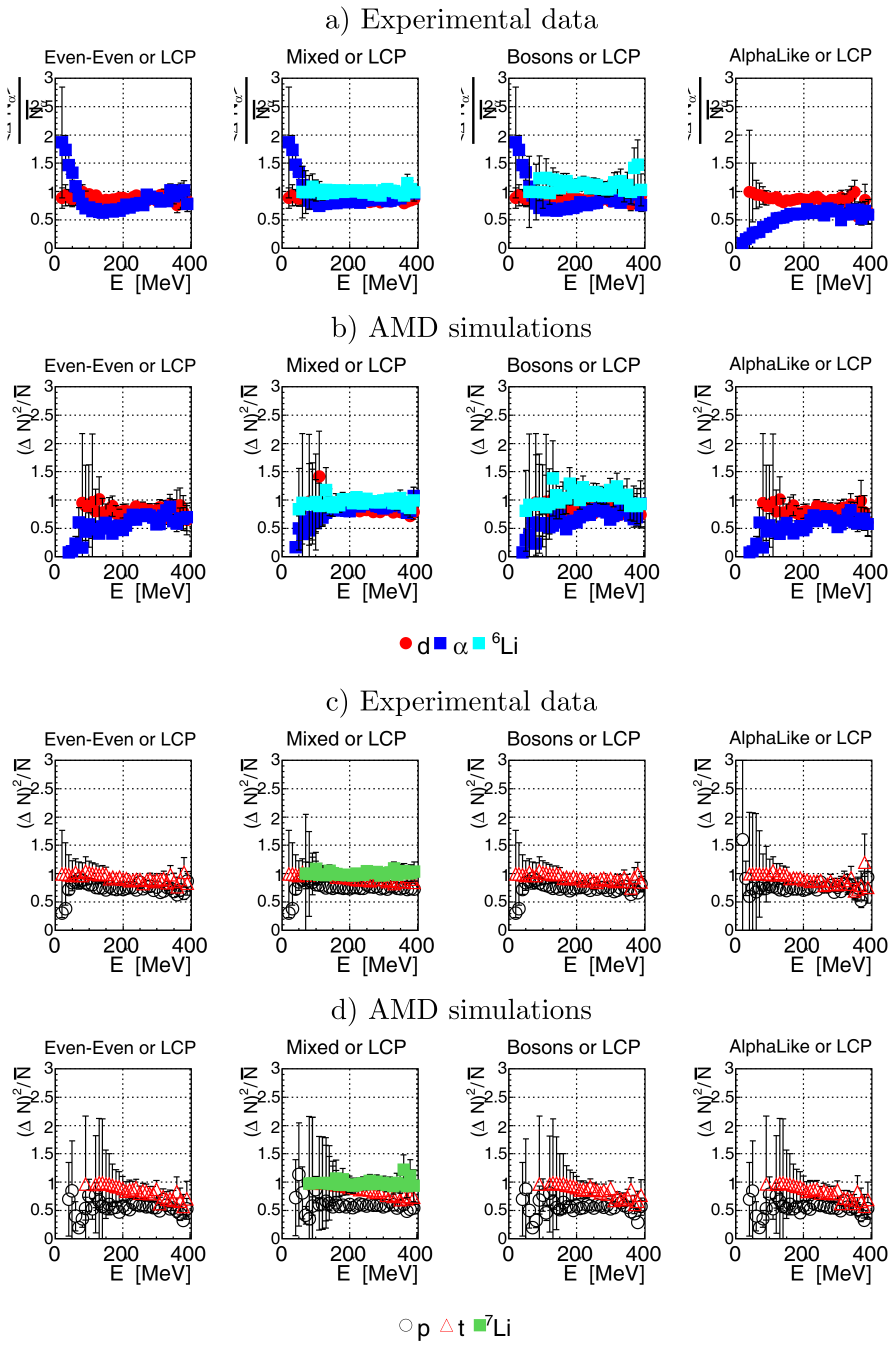

Figure 2: Multiplicity fluctuations of bosons (a,b) and fermions (c,d), experimental data (a,c) and AMD calculations (b,d).

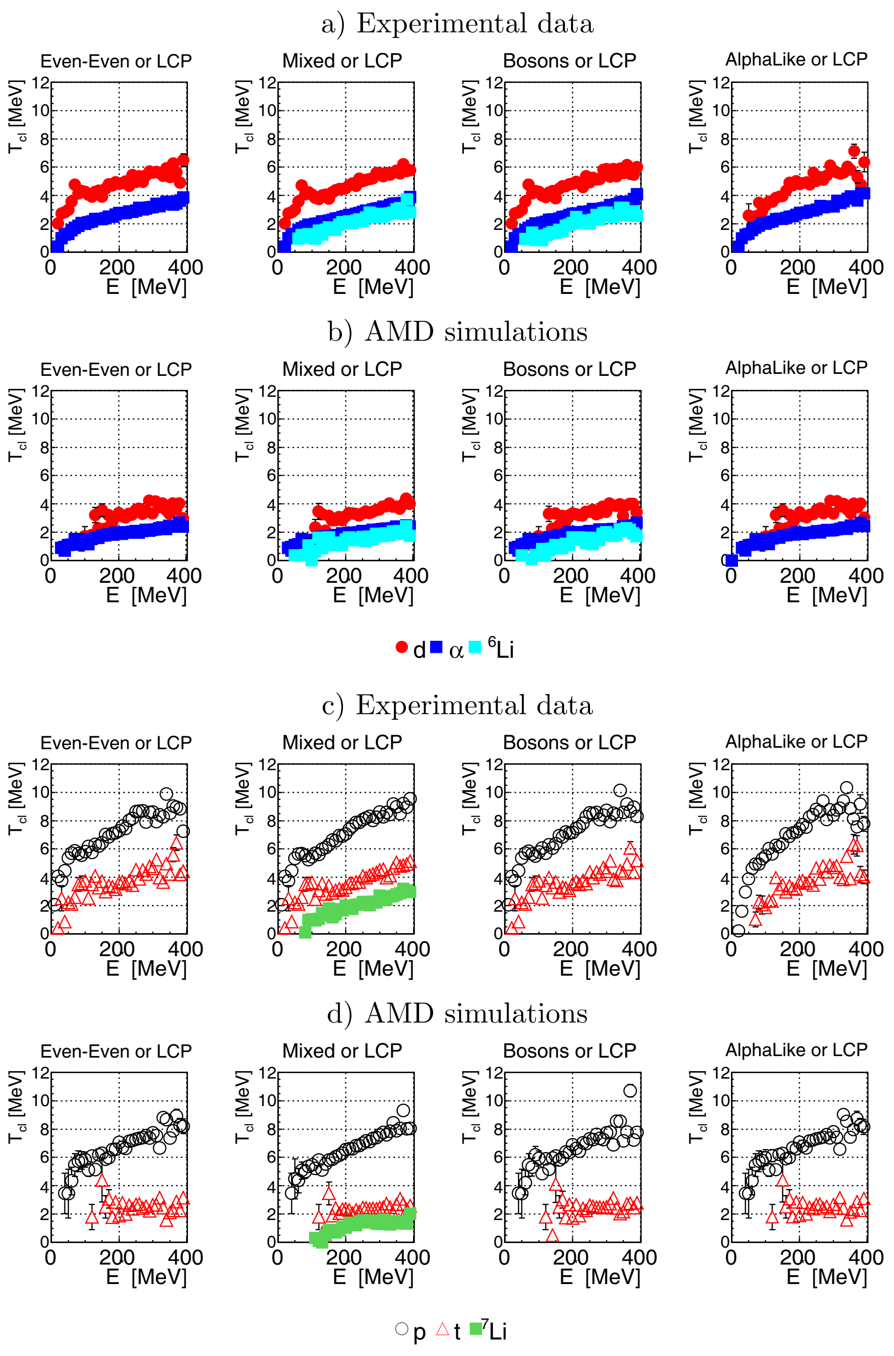

Figure 3: Temperature of bosons (a,b) and fermions (c,d), experimental data (a,c) and AMD calculations (b,d).

multiplicity fluctuations of bosons and fermions for each type of matter as a function of excitation energy E* calculated through calorimetry are presented. Panels a, c refer to experimental data, b,d to AMD calculations. In the experimental data the enhancement of multiplicity fluctuations is observed for low excitation energies for 3 types of matter: even - even, bosons and mixed. Whether those events are the candidates for Bose-Einstein condensates is an open issue. Multiplicity fluctuations higher than the classical limit are not observed for alpha-like matter or for all other types of matter in the AMD calculations, where we can observe the suppression of multiplicity fluctuations.

5 Momentum fluctuations

A method for measuring the temperature based on momentum quadruple fluctuations of detected particles was proposed in [15]. A quadruple moment $Q_{xy} = p_x^2 - p_y^2$ is defined in a direction transverse to the beam axis (z-axis) to minimize non-equilibrium effects [3] [4] [5]. The average Q_{xy} is zero for a given particle type in the center of mass of the equilibrated emitting source. In the Figure 3 the temperatures extracted for bosons and fermions using the method described in [15] are presented as a function of excitation energy. It can be noticed that the temperature of bosons is lower than the fermions and the temperature of bosons extracted from experimental data is higher than extracted from AMD simulations. It is interesting, that the temperature extracted for tritons from AMD data does not show a dependence on the excitation energy. The temperatures of protons from both the experiment and from the simulation are very similar.

6 Summary

The multiplicity fluctuations and the momentum quadrupole fluctuations for bosons and fermions for different classes of events, selected on the basis of exit channel spins, have been studied. Differences between the experimental results and predictions of theoretical calculations have been noticed in both observables. It is highly recommended to compare the experimental results with a model that takes the quantum nature of emitted fragments into account. In future analyses we plan to incorporate the quantum and Coulomb corrections to density and temperature determinations as proposed in [2].

We acknowledge support from the United States Department of Energy under Grant No. DE-FG03-93ER40773 and the Robert A. Welch Foundation under Grant No. A0330

References

[1] Zheng H., Giuliani G., Bonasera A. Nuclear Science and Techniques **24** (2013) 050512

[2] Zheng H., Giuliani G., Bonasera A. Phys Rev C **88** (2013) 024607

[3] Zheng H. and Bonasera A. Phys Lett B **696** (2011) 178181.

[4] Zheng H. and Bonasera A. Phys Rev C **86** (2012) 027602

[5] Zheng H., Giuliani G., Bonasera A. Nucl Phys A **892**(2012) 4357.

[6] Ono A. et al Phys. Rev. C **53** (1996) 2958

[7] Ono A. Phys. Rev. C **59** (1999) 853

[8] Charity R. J. et al Nucl. Phys. A **483** (1988) 371

[9] Schmidt K. et al J. Phys.: Conference Series **420** (2013) 012088

[10] Tarnowsky T J. J. Phys. G: Nucl. Part. Phys. **38** (2011) 124054

[11] Hwa R C, Yang C B. Phys. Rev. C **85** (2012) 044914

[12] Friman B, Karsch F, Redlich K et al. Eur. Phys. J. C (2011) 1694

[13] Gorenstein M I. Phys. Part. Nucl. **39** (2008) 1102-1109

[14] Konchakovski V P, Gorenstein M I, Bratkovskaya E L. Indian J. Phys.**85** (2011) 1-4

[15] Wuenschel S, Bonasera A, May L W, et al. Nucl Phys A **843** (2010) 113.