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Indications of Bose-Einstein condensation and Fermi quenching in the decay of hot nuclei

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Summary. — We report experimental signals of Bose-Einstein condensation and Fermi quenching in nuclear systems at low excitation energies produced in ^{40}Ca + ^{40}Ca collisions. The innovative experimental setup, constituted by the coupling of the VAMOS spectrometer to the 4π charged particle detector INDRA, allowed us to reconstruct the characteristics of the decaying hot source. We have investigated the thermodynamic properties, temperatures and partial nucleon densities, of the low density region of the nuclear system with quantum fluctuation analysis techniques, as "seen" by bosons and fermions separately. We show that in dilute hot nuclear systems, as in atomic traps, bosons experience a higher density than fermions do. Also, the nuclear interaction between fermions and bosons does not significantly reduce the fermion quenching and the Bose condensation.

1. – Introduction

Significant theoretical and experimental efforts in different fields of physics has been stimulated by the study of quantum systems composed of mixtures of bosons and fermions. In nuclear physics, nuclei are commonly described as systems of strongly interacting fermions, namely neutrons and protons. However, a picture of nuclei as systems composed of bosonic clusters, such as α (^{4}He) particles can explain some observed phenomena. A renewed interest for the searching of signatures of boson condensation

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phenomena in nuclear systems has recently appeared [1-4] and it has been suggested that boson condensates may be produced in hot finite nuclear systems produced in heavy-ion collisions [5]. In collisions at intermediate beam energies ($E/A = 15$–$50\,\mathrm{MeV}$) one can excite finite nuclear systems that evolve by decaying into one or more complex fragments ($Z > 2$), commonly associated to "liquid drops", and light particles ($Z \leqslant 2$), commonly associated to a "gas-like" phase. The so-produced systems may contain mixtures of fermions and bosons in a dilute gas-like phase.

In this work we investigate signals of nuclear BEC in the decay of excited quasi-projectile nuclear systems produced in semi-peripheral Ca+Ca collisions at $E/A = 35\,\mathrm{MeV}$, detected by a novel experimental setup, combining a 4π detector array and a high resolution magnetic spectrometer. The obtained results show analogies with similar phenomena observed in atomic traps [6], thus providing possible interesting links between atomic and nuclear physics.

2. – The experiment and event selection

The experiment was performed at the cyclotrone at the Grand Accelerateur National d'Ions Lourds (GANIL). ^{40}Ca beam at 35 MeV/nucleon energy was impinged on isotopically enriched ^{40}Ca target. Charged reaction products emitted at angles $\theta = 7°$–$176°$ were detected and identified in charge, mass and kinetic energy by the 4π detector INDRA [7]. At very forward angles ($\theta < 7°$) the heavy residue originated from the decay of excited quasi-projectiles (QPs) were detected in the large acceptance and high resolution VAMOS magnetic spectrometer [8]. A detailed description of the detectors and their coupling can be found in [9].

This setup allowed to reconstruct, on an event-by-event basis, the mass, charge and excitation energy of the QP system, and to characterize its decay channels. The present analysis focuses on peripheral and semi-peripheral collisions.

Velocity selections were applied on the detected particles, to remove fragments from non-QP sources [10]. With this procedure one can deduce the charge (Z_{QP}), mass (A_{QP}) and momentum ($\vec{p}_{QP}$) of the QP before its decay. The so-called transverse excitation energy ($E^\star$) [11,12] was calculated through calorimetry, and events were then sorted in 13 excitation energy bins, 0.5 MeV/nucleon wide, from 0 to 6.5 MeV/nucleon. Events with a reconstructed QP mass between 34 and 46 were selected, to provide high statistics. Specific constraints on the quadrupole moment of the emitted particles momentum distribution [12-15] allowed us to isolate events with, on average, isotropic emission. These events are therefore characterized by a certain degree of equilibration.

3. – Analysis and results

A quantum fluctuation analysis technique, based on the study of particle quadrupole momentum, multiplicity fluctuations, and mean multiplicities, experimentally measured, allows us to estimate the temperatures and densities of the produced systems [11, 16, 17]. The method takes into account the fermionic and bosonic nature of the particles, as well as Coulomb repulsion between them [18, 19].

In fig. 1 we plot the extracted "local partial nucleon densities", defined as the density "seen" by a specific "probe particle" (namely protons, deuterons, and alphas), normalized to their saturation density, ρ_0, as a function of the excitation energy per nucleon E^*/A. It is important to remind that these local densities refer to the density of the dilute phase (gas-like) produced by the de-excitation of the hot QP system. The extracted values open

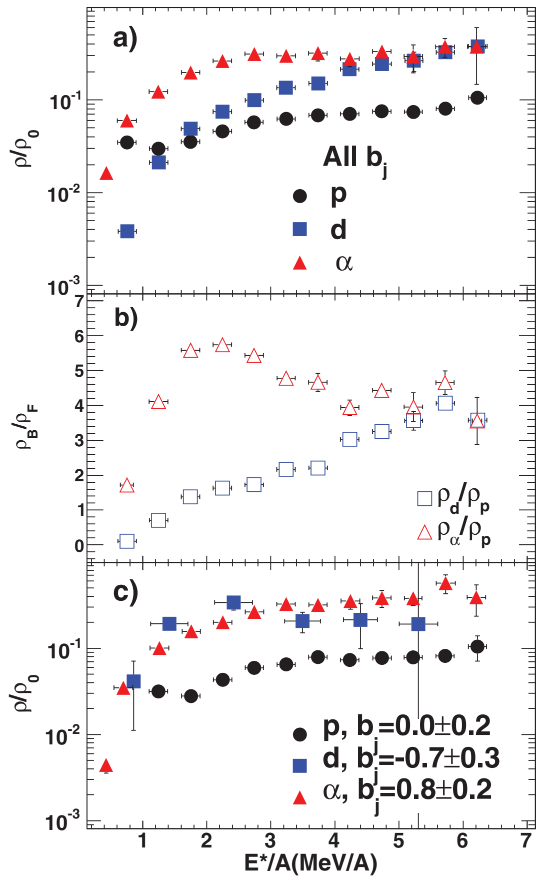

Fig. 1. – (a) Partial densities *vs.* transverse excitation energy per nucleon extracted from proton, deuteron and α fluctuations. (b) Boson-to-fermion density ratio. (c) Same as panel (b) with gates applied to select quasi-purely boson/fermion events (see text).

the possibility of observing differences between local densities extracted with bosons (d and α) and local densities extracted with fermions (p), and relate them to a possible BEC phenomenon.

As the excitation energy increases, the reduced local nucleon densities seen by protons and alphas increase and saturate at $\simeq 2$ MeV/nucleon around $0.07\rho_0$ and $0.3\rho_0$, respectively. This is not observed for deuterons: their densities are close to those extracted with fermions (protons) at low E^*, while they approach the densities seen by α's at higher E^*. As shown in fig. 1(b), a factor between 4 and 6 is observed between the fermion (p) and the α local densities at each energy (and up to 4 for d) and densities seen by protons are systematically smaller than those seen by bosons above 1 MeV excitation energy. Similarly to what observed in atomic traps, while bosons experience higher density values and seem to condense, fermions, due to the Pauli principle, tend to move apart, experiencing lower density values. In the case displayed in panel (a) of fig. 1, each event is a mixture of interacting fermions and bosons. In order to shed more light, we separate bosonic-like events and fermionic-like events by means of the strategy suggested in ref. [18]. It allows us to isolate events mostly dominated by the emission of bosons or fermions.

Figure 1 (panel (c)) shows the extracted partial density, ρ/ρ_0, as a function of excitation energy, E^*/A, as seen by protons in p-like events, by deuterons in d-like events and by alphas in α-like events. A remarkably good agreement for all the excitation energies is observed for the densities seen by bosons, which are higher than the densities seen by fermions. These results shed more light on the observations presented in panel (a) of the same figure.

Indeed, the nucleon densities seen by α's and protons in α-like and p-like events (panel (b)) are very similar to the ones plotted in panel (a) and corresponding to events containing mixtures of bosons and fermions. This suggests that both in purely boson-like events and in events where mixtures of bosons and fermions are emitted, bosons experience higher densities as compared to fermions. The signals pointing to the existence of a boson condensation phenomenon are independent of the presence of fermions, who do not prevent α particles to condensate. Similar considerations hold for fermions: the observed fermion quenching in a mixture of fermions and bosons is not reduced by the presence of bosons with their mutual nuclear interaction. These results recall what has been recently observed in atomic systems [6]. A detailed analysis of other signals indicating a phenomenon of condensation of boson in the decay of excited ^{40}Ca nuclei can be found in [20].

4. – Conclusions

In summary we have investigated the decay of excited QP nuclear systems produced in semi-peripheral ^{40}Ca+^{40}Ca collisions at $E/A = 35$ MeV, detected with the innovative INDRA-VAMOS setup. Within the selected events, quantum fluctuation methods allowed us to estimate local partial densities as seen by bosons (deuterons and alphas) and by fermions (protons) in the low density gas-like phase. We have selected classes of events where the low density region, produced in the decay of the quasi-projectile, is purely composed by either bosons or fermions and classes of events with mixtures of both types of particles. The observed results seem to provide evidences that fermions experience a lower density than bosons do. We associate these observations to signals of boson condensation and fermionic quenching phenomena in excited finire nuclear systems. The reciprocal interactions between fermions and bosons, present in events where mixtures of bosons and fermions coexist, does not seem to reduce the observed boson condensation and fermion quenching. Nuclear boson condensation phenomena may play a key role on the recently explored effects of alpha-clusterization in very dilute nuclear matter and on the density dependence of the symmetry energy [21, 22]. Possible future measurements with femtoscopy techniques [23] may provide further insights into the dynamical features of the observed phenomena. Finally, we also highlight the similarity of our observations with those published on [6] where condensation and Fermi quenching for atomic systems were studied. These similarities stimulate also possible interdisciplinary studies involving both atomic and nuclear systems, regardless the different interactions, number of constituents and sizes involved.

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