Signals of Bose Einstein condensation and Fermi quenching in the decay of hot nuclear systems

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We report experimental signals of Bose-Einstein condensation in the decay of hot Ca projectile like sources produced in mid-peripheral collisions at sub-Fermi energies [1]. The experimental setup, constituted by the coupling of the INDRA 4π detector array to the forward angle VAMOS magnetic spectrometer, allowed us to reconstruct the mass, charge and excitation energy of the decaying hot projectile-like sources. Furthermore, by means of quantum fluctuation analysis techniques, temperatures and mean volumes per particle as seen by bosons and fermions separately are correlated to the excitation energy of the reconstructed system. The obtained results are consistent with the production of dilute mixed (bosons/fermions) systems, where bosons experience a smaller volume as compared to the surrounding fermionic gas. Our findings recall similar phenomena observed in the study of boson condensates in atomic traps.

Only peripheral and semi-peripheral collisions, leading to a heavy QP remnant detected in VAMOS with $Z > 5$ have been studied in this work. In order to reconstruct the charge, Z_{QP}, mass, A_{QP}, and momentum vector $\mathbf{p}_{QP}$, of the QP, particles with $Z = 1$, 2 and $Z \geq 3$, detected by INDRA were attributed to QP decay when their longitudinal velocities lay within the range of ±65%, ±60%, ±45%, respectively, of the coincident QP residue velocity. In order to shed more light into these observations, we try to separate bosonic-like events and fermionic-like events by means of the following event-by-event quantity:

$$b_j = \frac{1}{M}\sum_{i=1}^{M}\frac{(-1)^{N_i}+(-1)^{Z_i}}{2}$$

where M is the event multiplicity and Z_i and N_i are the charge and neutron numbers of the i^{th} fragment, respectively. b_j is equal to 1, − 1 and 0 when all fragments emitted in the event are Z even-N even, Z odd N odd, and A-odd, respectively. The temperatures and local volumes of the produced systems can then be estimated by studying the measured particle quadrupole momentum and multiplicity fluctuations, as well as mean multiplicities, according to the quantum fluctuation analysis techniques. In Fig.1, we showed the critical temperature T_0 as function of density for both mixture and boson-like events (the lines indicate the ideal boson gas result). Values of the order of few MeV are obtained for both particles, in agreement with theoretical predictions. The experimentally derived values are systematically higher both for d and α as compared to the ideal case. This is expected because the Coulomb repulsion enhances the condensate. It is important to remark that at high density, and especially for the case (d displays unfortunately large error bars due to poor statistics), the data are closer to the ideal case. This is due to the increased importance of the nuclear force which reduces the Coulomb repulsion.

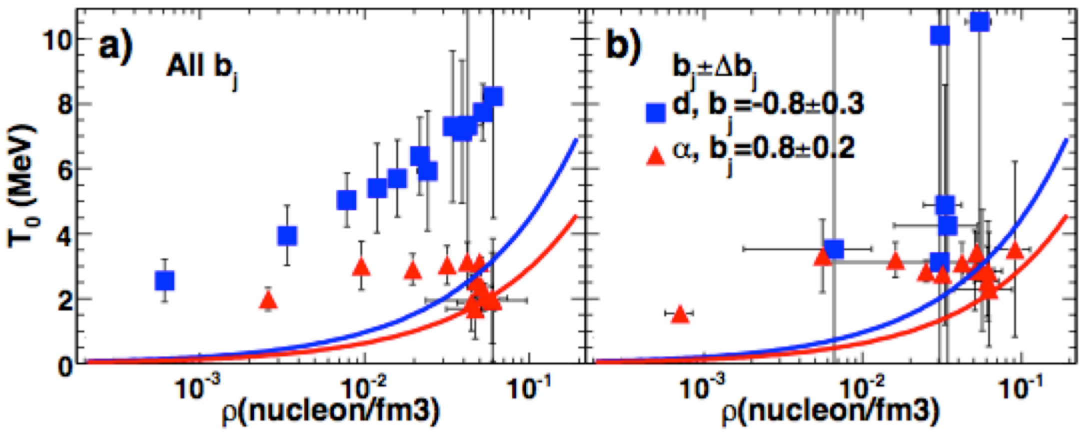

FIG. 1. Critical temperature vs local density for (a) mixture and (b) boson-like events.

In summary we have studied the decay of ex-cited quasi-projectile systems produced in mid-peripheral Ca40+Ca40 collisions at E/A = 35 MeV with the INDRA-VAMOS setup. Within the selected events, mean partial volumes per particle and temperatures, probed by bosons (deuterons and alphas) and by fermions (protons) in the low density gas-like phase have been estimated with quantum fluctuation methods. The observed results show that bosons experience a smaller volume and a higher energy density than fermions. These results may be associated to the presence of boson condensation and fermionic quenching phenomena in nuclear systems. Condensation temperatures are in agreement with theoretical predictions. These phenomena are observed even in events where mixtures of bosons and fermions coexist, suggesting that they are not reduced by boson-fermion interactions. The results of this work recall closely similar phenomena observed in atomic systems where the coexistence of a quasi-pure Bose Einstein condensate of Li7 atoms (bosons) in a Fermi sea of Li6 (fermions) was observed [2]. This interdisciplinary analogy seems to indicate a similar nature for processes occurring in atomic scale and nuclear scale quantum systems, regardless of their different sizes and characteristic interactions. Future investigations on implications of these phenomena on α clustering and symmetry energy at low density also stimulate using particle-particle correlations to estimate emission densities and volumes.

[1] P. Marini *et al.*, arXiv: 1501.00595.

[2] F. Schreck, L. Khaykovich, K.L. Corwin, G. Ferrari, T. Bourdel, J. Cubizolles, and C. Salomon, Phys. Rev. Lett. **87**, 080403 (2001).