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

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ABSTRACT

We report on first experimental observations of nuclear fermionic and bosonic components displaying different behaviours in the decay of hot Ca projectile-like sources produced in mid-peripheral collisions at sub-Fermi energies. The experimental setup, constituted by the coupling of the INDRA $4\pi$ detector array to the forward angle VAMOS magnetic spectrometer, allowed to reconstruct the mass, charge and excitation energy of the decaying hot projectile-like sources. By means of quantum-fluctuation analysis techniques, temperatures and local partial densities of bosons and fermions could be correlated to the excitation energy of the reconstructed system. The results are consistent with the production of dilute mixed systems of bosons and fermions, where bosons experience higher phase-space and energy density as compared to the surrounding fermionic gas. Our findings recall phenomena observed in the study of Bose condensates and Fermi gases in atomic traps despite the different scales.



The study of quantum systems composed of bosons and fermions stimulates significant theoretical and experimental effort in different fields of physics. For instance, investigations of quantum systems presenting mixtures of bosons and fermions, with the outstanding example of $^3$He–$^4$He fluids, have led to the observation of Bose–Einstein condensation (BEC) and Fermi quenching (FQ) [1,2]. In nuclear-physics experiments we observe the existence of phenomena that can be explained by considering nuclei as systems whose properties are ascribed to the fact that they are composed of bosonic clusters, the most important being $\alpha$ particles, arising from a reorganisation of their fundamental fermionic constituents, protons and neutrons [3–8]. If the nucleus is composed of fermions and bosons, one may wonder whether the bosonic properties may dominate over the fermionic properties in some instances, such as for the Hoyle state in $^{12}$C. Along this direction [9–11], it has been suggested that Bose-condensate sig-

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natures may be observed in hot nuclei produced during heavy-ion collisions [12]. The present article aims at identifying different signals from bosons and fermions with the purpose of investigating BEC phenomena in the decay of excited quasi-projectile systems produced in semi-peripheral Ca + Ca collisions at $E/A = 35$ MeV. The results display analogies with phenomena observed in atomic traps [2], suggesting links between atomic and nuclear physics phenomenologies.

The experiment was performed at the Grand Accélérateur National d'Ions Lourds (GANIL). $^{40}$Ca targets were bombarded with $^{40}$Ca beams at 35 MeV/nucleon. An innovative setup, constituted by 288 telescopes of the $4\pi$ detector INDRA [13], covering angles $\theta = 7°–176°$, and by the large acceptance and high resolution VAMOS magnetic spectrometer [14] at very forward angles ($2° < \theta < 7°$), which triggers the data acquisition, was used for this study. The combined setup [15] allowed to reconstruct the mass, charge and excitation energy of the quasi-projectile (QP) system, and to characterise its decay channels on an event-by-event basis. Such decay leaves the system with a forward moving QP residue, detected and identified in charge and mass with the VAMOS spectrometer, and coincident light particles and fragments emitted at larger angles and detected by INDRA telescopes. Only peripheral and semi-peripheral collisions, leading to a heavy QP residue with $Z > 5$ detected in VAMOS, are discussed therein. To reconstruct the charge, $Z_{QP}$, mass, $A_{QP}$, and momentum vector, $\vec{p}_{QP}$, 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 [16]. This selection is intended to remove fragments from non-QP sources [17]. To minimise contributions from entrance-channel effects, predominant in the beam direction, we have estimated the excitation energy, $E^\star/A$, of the reconstructed QPs from the momenta ($\vec{p}_\perp$) of their accompanying emitted particles transverse to the quasi-projectile momentum. This allowed to extract transverse excitation energy, $E^\star$, through calorimetry as the sum of the charged particle transverse kinetic energy in the QP reference frame ($K^i_\perp$), corrected for the reaction $Q$-value: $E^\star = \frac{3}{2}\sum_i K^i_\perp - Q_{value}$ [18].

Events with a reconstructed QP mass between 34 and 46 were selected, which correspond to a QP charge distribution centred at $Z_{QP} = 20$ and with a standard deviation of about 1 unit. The reconstructed mass $A_{QP}$ does not account for the emitted (not detected) neutrons. However, simulations performed with a statistical decay model (the code GEMINI [19] was used) show that the evaporation of Ca QPs at these measured excitation energies mostly produces an average neutron multiplicity $M_n \lesssim 1$. This is due to the fact that the $\alpha$ (proton) emission is energetically favoured with respect to neutron emission for all the selected Ca isotopes heavier (lighter) than $^{40}$Ca (with the exception of $^{45,46}$Ca). The uncertainty on $E^\star/A$ due to the non-detection of neutrons is within the chosen $E^\star/A$ bin width (0.5 MeV/nucleon) in figures displayed in this article.

Fig. 1(a) shows the measured multiplicity of different light particles as a function of the reconstructed transverse excitation energy of the QP. In panel (b) we also show the evolution of the charge, $Z_{max}$, of the largest fragment left by the decay of the QP, which is similar to previous works [20]. To isolate events with isotropic emission, i.e. characterised by a certain degree of equilibration, we place a selection on the longitudinal momentum ($p^i_z$) and transverse momentum ($p^i_\perp$) of the fragments comprising the QP: $-0.3 \leq \log_{10}(Q_{shape}) \leq 0.3$ where $Q_{shape} = \sum_i (p^i_z)^2 / \sum (p^i_\perp)^2$, with the sum extending over all fragments of the QP. This selection allows to remove events where the kinetic-energy spectra of the emitted particles differ from an exponential and present a high energy tail, likely due to a remaining contribution from mid-rapidity emission. Among the studied particles, $\alpha$ particles are the most af-

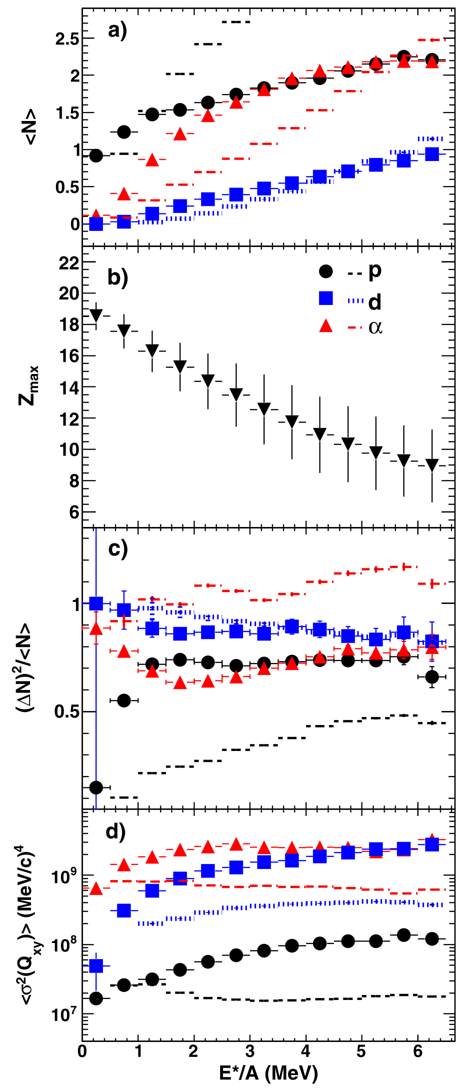


**Fig. 1.** (Colour online.) (a) Measured mean multiplicity of protons, deuterons and alphas; (b) charge of the largest fragment; (c) multiplicity fluctuations and (d) quadrupole momentum fluctuations of particles emitted by QPs as a function of their transverse excitation energy per nucleon, $E^\star/A$. Results obtained for GEMINI data are shown as dotted lines.

fected by this selection. Its impact on the observables presented here (in particular temperatures and densities) will be discussed in the following.

In Fig. 1(c) we present the multiplicity fluctuations, $(\Delta N)^2/\langle N\rangle$, for protons ($p$), deuterons ($d$) and alphas ($\alpha$) as a function of $E^\star/A$. Significant differences exist between fermions and bosons at low $E^\star$. In a system where the quantum nature of these particles could be neglected, their multiplicity fluctuations would be at the classical limit $(\Delta N)^2/\langle N\rangle = 1$ [21]. However, in our data we observe that they are all below such limit. For fermions this phenomenon is known as fermion quenching and has been observed in trapped Fermi gas and heavy-ion collisions [22,23]. For bosons $(\Delta N)^2/\langle N\rangle$ is expected to diverge near the critical temperature, $T_0$, for the Bose–Einstein condensation, even though finite-size effects, or a repulsive force among bosons, might smoothen the divergence [21]. In our case, $(\Delta N)^2/\langle N\rangle < 1$ corresponds to a temperature region around and below the critical point, where a condensate could form.

Significant differences, up to about 2 orders of magnitude, can also be observed between fermions and bosons in the quadrupole