Competition between fermions and bosons in nuclear matter at low densities and finite temperatures

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We derive the free energy for fermions and bosons from fragmentation data. Inspired by the symmetry and pairing energy of the Weizsacker mass formula, we obtain the free energy of fermions (nucleons) and bosons (alphas and deuterons) using Landau's free energy approach. We confirm previously obtained results for fermions and show that the free energy for alpha particles is negative and very close to the free energy for ideal Bose gases and in perfect agreement with the free energy of an interacting Bose gas under the repulsive Coulomb force. Deuterons behave more similarly to fermions (positive free energy) rather than bosons, which is probably due to their low binding energy. We show that the alpha particle fraction is dominant at all temperatures and densities explored in this work. This is consistent with their negative free energy, which favors clusterization of nuclear matter into alpha particles at subsaturation densities and finite temperatures.

Introduction

Dilute mixed systems composed of fermions and bosons exhibit a large variety of interesting features that have been the subject of several theoretical and experimental works. Although generally considered as made of strongly interacting fermions (protons and neutrons), nucleonic systems have been observed to display some properties relevant of bosons. Some of these aspects are the alpha decay in heavy nuclei, preformed alpha particles in the ground state of nuclei, and the cluster structure of N = Z = even light nuclei. While the tunneling through the Coulomb barrier is well understood, the preformation of the alpha particle is still a difficult task for theoretical model descriptions. Recently, ab initio lattice simulations have shown that, depending on the form of the interaction between nucleons, the ground states of certain light nuclei lie near a quantum phase transition between a Bose-condensed gas of alpha particles and a nuclear liquid [1].

We report on experimental free energy (density) for fermions and bosons from the fragmentation of quasiprojectiles by application of Landau’s free-energy approach [2]. The temperature and density of the produced quasiprojectile systems are determined using the quantum fluctuation method. We notice, and it is an important result, that the free-energy density for alphas is negative. In contrast, it is positive for deuterons and close to that for fermions. The free-energy density for ideal Bose gases gives results similar to those for alphas but has opposite sign for those of deuterons. This demonstrates that alphas behave indeed as bosons while deuterons do not and are suppressed, probably due to their low binding energy. The fact that the free-energy density is negative means that if N = Z = even systems will “live” long enough, all the particles will cluster into alphas while deuterons will disappear.

Results

The experiment was performed at the Cyclotron Institute, Texas A&M University. Beams at 35 MeV/A of ^{64}Zn, ^{70}Zn, and ^{64}Ni from the K-500 superconducting cyclotron were used to respectively irradiate self-supporting targets of ^{64}Zn, ^{70}Zn, and ^{64}Ni.

We have analyzed fragment yield data to investigate the nuclear phase transition using the Landau free-energy technique. The temperatures and densities of the QP are determined from the fluctuations of the transverse momentum quadrupole, average multiplicities, and multiplicity fluctuations. These observables are used to correct for Coulomb effects as well.

Using the extracted Landau's fitting parameters, to determine the fragment free energy per nucleon, FA, for fermions. For bosons (deuterons and alphas), we adopt the parametrization FA = −apδ/A3/2 to easily derive the free energy [2]. Estimated statistical errors on FA for protons are 10% while those for deuterons and alphas are smaller than 3%. There is a strong correlation of increasing FA with increasing T and density for protons and deuterons. In contrast to protons and deuterons results, FA values for alphas are negative and weakly depend on T and density. In Fig. 1 the free energy density against T is examined. It is observed that f_A approaches zero in the limit T → 0 MeV, as expected. Both the f_A results obtained for an ideal Bose gas (dashed lines) and for a Coulomb corrected Bose gas (solid lines) are shown.

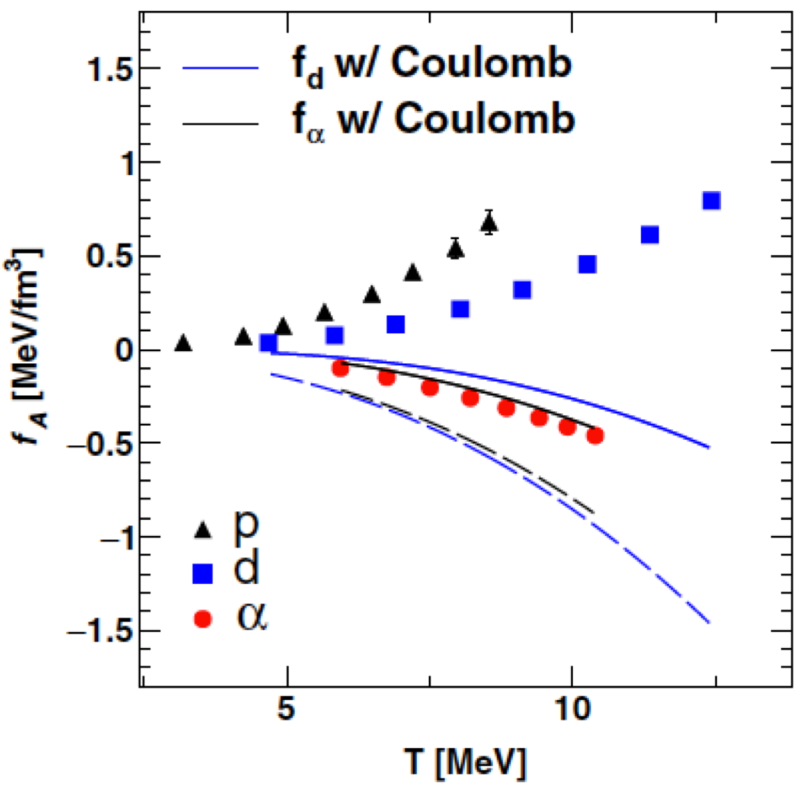

FIG. 1. Free-energy density as a function of temperature for the three light particles. Error bars are shown when statistical errors exceed the size of the symbols. Solid lines refer to the Coulomb corrected free-energy density for deuterons and alphas. The dashed lines are the corresponding ideal Bose gas limit.

The good agreement between the calculations and the experimental results is quite interesting since they have been obtained in completely different ways, one from the experimental yield distribution and the other from the Coulomb corrected free energy density for bosons. The ideal gas limit displays a similar behavior of the data but slightly shifted downwards. Notice also the different theoretical behavior of deuterons and alphas with and without Coulomb corrections. The positive experimentally derived fA values for deuterons indicate that these particles behave much like fermions, probably because of their low binding energy. For a system in equilibrium, this implies that the system of nucleons will predominantly coalesce into alpha particles.

In theoretical models cluster mass fractions are commonly used to characterize the degree of clusterization in low-density matter. We also investigate the mass fractions of the three light particles as a function of E*/A, derived directly from data. While a higher alpha-cluster fraction is seen for all E*/A values, protons and deuterons have similar mass fractions.

Conclusions

In summary, we have extracted the free energy (density) for fermions and bosons in finite nuclei at subsaturation densities and finite temperatures using the Landau free-energy technique. It was found that free-energy results for alpha particles are negative and close to those of ideal (and Coulomb corrected) Bose gases, whereas deuterons behave much like fermions. The alpha particle fraction was shown to be favored at all temperatures and densities explored in this work. The present results are consistent with the clusterization of nuclear matter into alpha particles. In the limit of zero temperature and ground-state density, the free energy discussed above reduces to the symmetry and pairing terms in the Weizsacker mass formula.

[1] S. Elhatisari *et al.*, Phys. Rev. Lett . **117**, 132501 (2016).
[2] J. Mabiala *et al.*, Phys. Rev. C **94**, 06461 (2016).