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MEAN-FIELD DESCRIPTION OF NUCLEI AT HIGH TEMPERATURE

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We propose and discuss a prescription suitable to include the contribution of continuum states in mean-field calculations at high temperature.

1. INTRODUCTION

Heavy ion collisions at intermediate energy have provided recently strong experimental evidence for the formation of highly excited thermalized nuclei, with temperatures of the order of five MeV[1]. In other recent analyses it has also been suggested that fragmentation data in high energy nucleus nucleus collisions may indicate the existence of a liquid gas phase transition in hot nuclei, with a transition temperature of about 15 MeV[2]. At such large temperatures equilibrated nuclei are conveniently described by the finite temperature Hartree-Fock equations[3,4]. One difficulty however is that continuum states in these equations lead to divergences, which cannot be ignored at high temperature. This difficulty is seen immediately when solving the thermal Hartree-Fock equations on a lattice. Indeed one finds in this case non vanishing occupation numbers for continuum states, which leads to constant nucleon distributions at large distance i.e. to a volume dependence of the results. The origin of this volume dependence is that thermal Hartree-Fock equations do not describe an isolated hot nucleus, which would be unstable against particle emission, but a hot nucleus in equilibrium with an external nucleon gas of evaporated particles. To extract the properties of the hot nucleus from a static Hartree-Fock calculation one thus needs to identify unambiguously the volume dependent contribution of the external nucleon vapor. In earlier calculations this problem was left

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out. Indeed numerical solutions were obtained either in an oscillator basis which cannot describe continuum states or in coordinate space including only bound and quasibound states, i.e. states bound by their Coulomb or centrifugal barriers[4]. These prescriptions look reasonable at low temperature but are inadequate to describe highly excited nuclei.

2. MEAN-FIELD CALCULATIONS OF HIGHLY EXCITED NUCLEI

In two recent publications[5,6] we have presented a prescription for isolating a hot nucleus from its vapor. The method is based on the existence of two distinct solutions of the Hartree-Fock equations for given values of the neutron and proton chemical potentials. The first solution corresponds to a hot nucleus surrounded by an external gas outside. In the second solution the density is nearly uniform and resembles that of a non interacting gas. Since nucleon distributions in these two solutions are found to coïncide at large distance it is possible to define the grand potential $\Delta\Omega$ of the hot nucleus as the difference of the grand potentials Ω (nucleus plus vapor) - Ω (vapor). The resulting quantity $\Delta\Omega$ is independent upon the radius R of the box in which calculations are being performed provided R is large enough.

In the presence of Coulomb forces some modifications have to be introduced because of the long range nature of these interactions. In reference 5 it was shown that in order to obtain a convergent prescription one must include the polarization of the vapor by the nucleus charge and remove the action of the Coulomb field of the vapor on the nucleus. A consistent may to perform this modification, based on a variational formulation can be found in reference 5 .

The importance of continuum effects can be seen in Figure 1, where our result for the nuclear entropy in lead-208 with interaction SIII as a function of temperature is compared with the contribution of the bound and quasi-bound states in the zero-temperature Hartree-Fock field. This figure also shows the result obtained when including continuum effects but using the zero-temperature mean-field. One can see that changes in the mean-field when temperature increases are also important. The result is an almost exact linear increase of entropy with temperature.

Further results of mean-field calculations can be found in references 5,6 concerning in particular the variation with temperature of various quantities such as radii, lifetimes, single particle spectra, nucleon distributions, up to temperatures of about 10 MeV. From these results one can conclude that earlier calculations without continuum contributions are valid up to 4 MeV but that large corrections arise beyond this value.

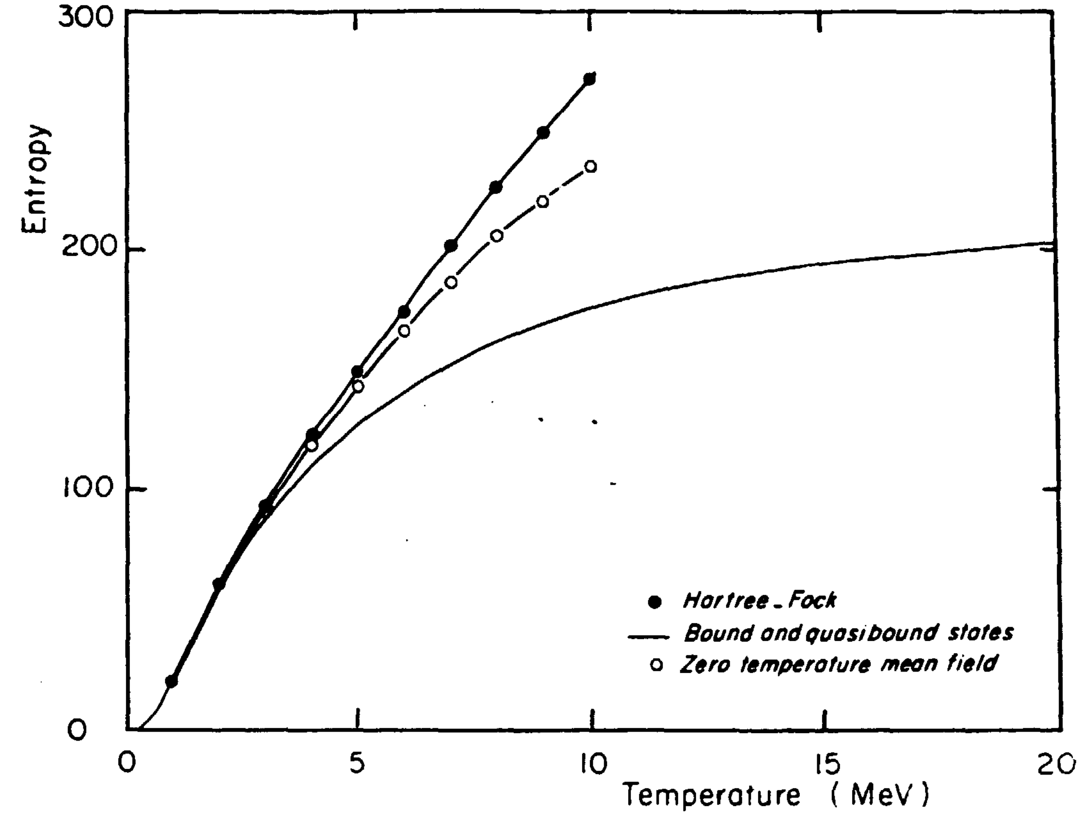

FIGURE 1
Entropy of lead-208 as a function of temperature calculated with interaction SIII. Hartree-Fock results are compared with the contribution of the zero-temperature mean-field, and with the contribution of bound and quasi-bound states.

3. STABILITY OF HOT NUCLEI

In numerical applications we found that the subtraction procedure described above cannot be extended beyond a certain limiting temperature. In practice this means that results beyond this value were depending upon the size of the cell. In such cases nucleons were found to leak outside the nucleus, which destroys the coïncidence between the densities in the nucleus plus vapor solution and in the vapor solution. The temperature at which this instability occurs depends strongly on the interaction used. In lead-208 it is about 8 MeV for interaction SKM but 11 MeV for interaction SIII[5]. Also it is larger by about 1 MeV for nuclei in the valley of stability than for neutron reach nuclei[6]. To understand the origin of this difference we performed in reference 6 a calculation of lead-208 without including Coulomb interactions. The result obtained for the nucleon distributions is shown in figure 2. It can be seen that in this case the nucleus still exists at 12 MeV temperature while it is disappearing at 8 MeV when Coulomb interactions are included.

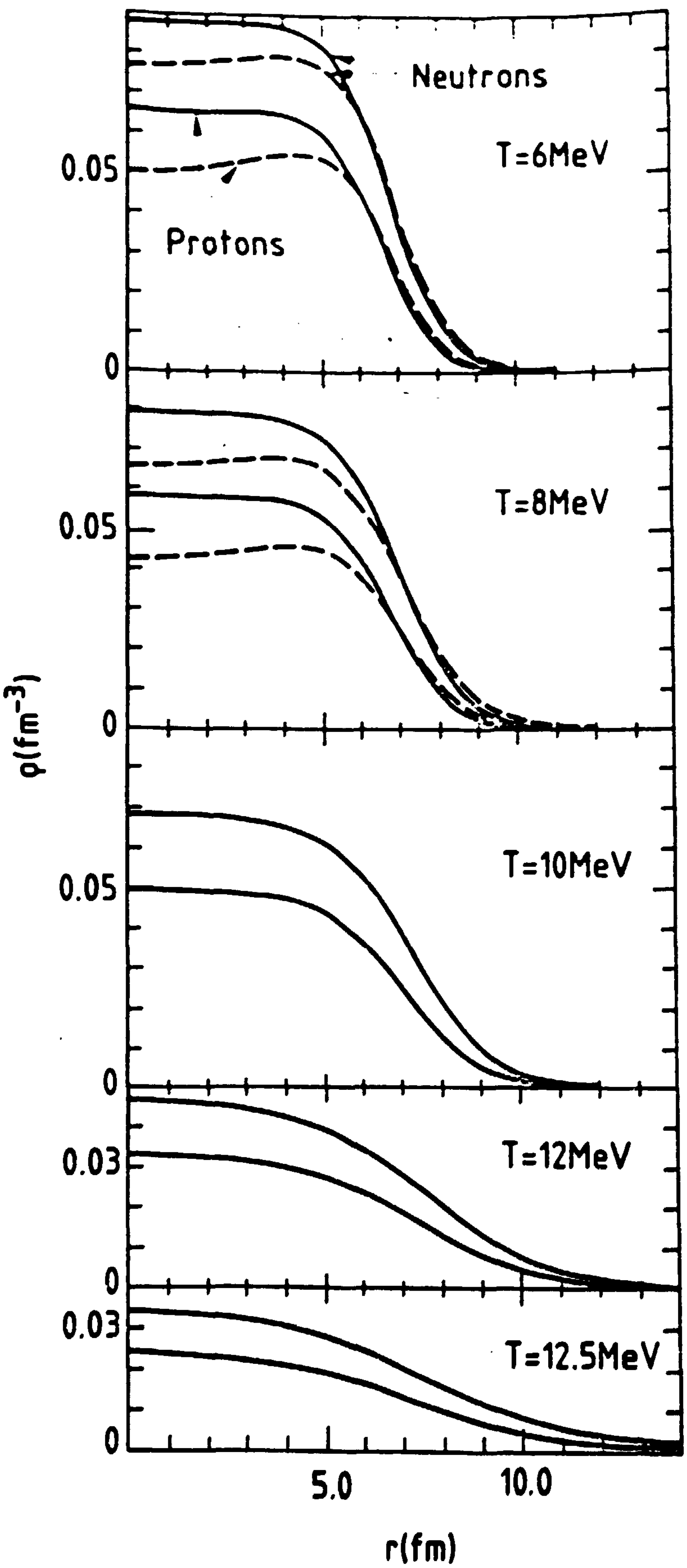

FIGURE 2
Subtracted neutron and proton density distribution calculated in lead-208 with interaction SIII and no Coulomb force, at various temperatures.

At high temperatures the nuclear radius becomes very large and the corresponding potential well also has a large radius while becoming very shallow. The resulting single particle levels become dense and move upwards. Eventually the nucleus is found to disappear.

4. CONCLUSION

The disappearance of the nucleus found in uncharged Hartree-Fock calculations at large enough temperatures should be interpreted as a manifestation of the liquid-gas transition in nuclear systems discussed in reference 2 . Indeed in our calculations without Coulomb forces a phase transition occurs when nucleus plus vapor and vapor solutions coïncide i.e. when an equilibrium between two distinct phases is no longer possible. This is a generalization to finite nuclei of the phase equilibrium discussed by the Illinois group[7,8] in the context of infinite and semi-infinite nuclear matter calculations. A comparison with such calculations, including the appropriate effective force and the appropriate neutron concentration is now under way.

When the Coulomb force is included, it induces an additional instability and the nucleus disappears around $T = 8$ MeV i.e. 5 MeV before the critical temperature obtained for uncharged lead-208. This additional instability should be reflected by a sharp decrease in the cross-section for compound nucleus formation. It is clear from our results that the effect of Coulomb forces on the stability of hot nuclei is important and must be included when analysing experimental data.

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