Effect of medium dependent binding energies on inferring the temperatures and freeze-out density of disassembling hot nuclear matter from cluster yields

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The decay of highly excited nuclear matter produced in heavy ion collisions is a complex dynamic process, which needs, in principle, a sophisticated treatment. One simple approach is the freeze-out concept in which the hot and dense matter in the initial stage is assumed to reach thermal equilibrium as long as reaction rates are high. With decreasing density, the reaction rates decrease and the equilibration process becomes suppressed. At that time the nuclear thermal and chemical equilibrium is frozen out. Often the description of the nuclear matter, in particular the distribution of clusters, is calculated within a statistical multifragmentation model assuming nuclear statistical equilibrium (NSE). Under the simplifying assumption that the final reaction product distribution is identical to the cluster distribution at the freeze out point, the thermodynamic parameters such as temperature T and particle number densities, n_n and n_p for neutrons and protons, respectively, can be reconstructed from the observed abundances. A simple method for extracting the temperature of the fragmenting hot system was given by Albergo, Costa, Costanzo and Rubbino (ACCR) [1]. The method is based on selecting double isotope (or isotone) ratios, R_2, such that the nucleon chemical potentials are eliminated leading to a relation between R_2, T and the binding energies of the isotopes (isotones). This method has been used in the analysis of a large number of experiments [2]. We point out [2] that the ACCR method was modified to account for: (i) the screening due to the Coulomb interactions among fragments in the freeze-out volume by using the Wigner-Seitz approximation; (ii) the effect of radial collective flow, and (iii) the effects of post emission decay (secondary decay) processes of particles and, in particular, γ which modify the freeze-out yield ratios. Without these corrections, different double ratios R_2 associated with selected sets of fragments (different thermometers) may result in significantly different temperature T (see a review in Ref. [2]).

If the freeze-out density is not very low the NSE will be modified by medium effects. In this work [3] we explore the abundance of light clusters in nuclear matter at subsaturation density. With increasing density, binding energies and wave functions are modified due to medium effects. The method of ACCR for determining the temperature and free nucleon density of disassembling hot nuclear source from fragment yields is modified to include, in addition to Coulomb effects and flow, also effects of medium modifications of cluster properties, which become of importance when the nuclear matter density is above 10^{-3} fm^{-3}.

Recent progress in the description of clusters in low density nuclear matter [4] enables us to evaluate the abundance of deuterons, tritons and helium nuclei in a microscopic approach, taking the influence of the medium into account. Within a quantum statistical approach to the many-particle system, we determine the single-particle spectral function, which allows calculation of the density of the nucleons as a function of the temperature and the proton's and the neutron's chemical potentials (T, μ_p, μ_n). The main ingredient is the self-energy $\Sigma(1,z)$, which is treated in different approximations. The single-particle

spectral function contains the single-nucleon quasiparticle contribution. Expressions for the single-nucleon quasiparticle energy $E^{qu}(p)$ can be given, for example, by the Skyrme mean-field parameterization. We note that in addition to the quasiparticle contribution, the contribution of the bound and scattering states can also be included in the single-nucleon spectral function, by analyzing the imaginary part of $\Sigma(1,z)$. Within cluster decomposition, A-nucleon T matrices appear in a many-particle approach. These T matrices describe the propagation of the A-nucleon cluster in nuclear matter. In this way, bound states contribute to the EoS, $n_\tau = n_\tau (T, \mu_p, \mu_n)$, see Ref [4]. In the low-density limit, the propagation of the A-nucleon cluster is determined by the energy eigenvalues of the corresponding nucleus. For the nuclei embedded in nuclear matter, an effective wave equation can be derived [4]. The A-particle wave function and the corresponding eigenvalues follow from solving the in-medium Schrodinger equation

$$
\left[E^{qu}(1) + \cdots + E^{qu}(A) - E^{qu}_{A\nu}(p)\right]\Psi_{A\nu p}(1\ldots A)
$$
$$
+ \sum_{1'\ldots A'} \sum_{i<j}\left[1 - \mathcal{F}(i) - \mathcal{F}(j)\right]V(ij,i'j')\prod_{k\neq i,j}\delta_{kk'}\Psi_{A\nu p}(1'\ldots A') = 0. \tag{1}
$$

This equation contains the effects of the medium in the single-nucleon quasiparticle shifts as well as in the Pauli blocking terms. It can be shown that the EoS can be evaluated as in the non-interacting case, except that the number densities of clusters must be calculated with the quasiparticle energies,

$$
n^{qu}(A,Z) = g_{A,Z}\int \frac{d^3p}{(2\pi)^3} f_{A,Z}\left[E^{qu}_{A,Z}(p)\right]. \tag{2}
$$

In the cluster-quasiparticle approximation, the EoS reads,

$$
n^{qu}_p\left(T,\mu_p,\mu_n\right) = \sum_{A,Z} Z n^{qu}(A,Z), \tag{3}
$$
$$
n^{qu}_n\left(T,\mu_p,\mu_n\right) = \sum_{A,Z}(A-Z)n^{qu}(A,Z), \tag{4}
$$

for the total proton and neutron densities, respectively.

Comparing the values of the parameters obtained in the full calculation, with inclusion of medium effects on the yields with those deduced in the ACCR approach, we find that moderate deviations in the temperature arise for densities larger than 0.0001 fm^{-3}. Determination of the densities is more sensitive to the medium effects. We thus conclude that the fragment yields from hot and dense nuclear matter produced in heavy ion collisions can be used to infer temperatures and proton/neutron densities of the early stages of the expanding hot matter. The assumption of thermal equilibrium can be only a first approach to this non-equilibrium process. To determine the yield of the different clusters, a simple statistical model neglecting all medium effects, i.e., treating it as an ideal mixture of non-interacting nuclei is not applicable when the density is larger than 0.0001 fm^{-3}. Self-energy and Pauli blocking will lead to energy shifts, which have to be taken into account to reconstruct the thermodynamic parameters from measured yields. The success of the simple ACCR method to derive the values for the temperature can be understood from a partial compensation of the effect of the energy shifts so that reasonable values

for the temperature are obtained also at relatively high densities. More care must be taken in inferring densities from the data.

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