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Theoretical Comparison of Different Thermometers for the Determination of the Nuclear Caloric Curve

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Abstract

The problem of the experimental determination of a nuclear temperature in heavy ion collisions is addressed within an extended Quantum Statistical Model which includes secondary evaporation from continuum states and an effective excluded volume interaction in the freeze out configuration. The comparison to experimental data from the INDRA collaboration suggests that thermodynamical equilibration can actually be reached even at excitation energies as high as 25 MeV/u, however final state interactions and side feeding can strongly deform the response of the different thermometers.

1 Introduction

With the increasing availability of quasi complete and exclusive data on the deexcitation of well identified single nuclear sources in heavy ion reactions [1], the longstanding challenge of studying nuclear thermodynamics is finally becoming a concrete possibility. The experimental evidences of a complete memory loss of the entrance channel [1] and the satisfactory comparison with statistical models based on thermodynamical equilibrium [2] suggest that in a wide range of incident energies and impact parameters the dynamical and thermodynamical components may

actually be decoupled, and that the application of physical concepts borrowed from macroscopic statistical mechanics, like thermal equilibrium, phase coexistence and phase transition, may be appropriate. Different thermometers have been proposed to study nuclear thermodynamics, namely slopes of light particle kinetic energy spectra [3], relative populations of excited states [4], double ratios of neighbour isotopes [5–7]. A cross comparison of average temperatures from populations of excited states and double ratios has given compatible results for the Ar+Au system at 35 MeV/u bombarding energy [8]. However this does not seem to be the case any more when data are analyzed more exclusively in different excitation energy bins. A striking example is given by the recent INDRA data for the Ar+Ni system at 95 MeV/u [9], where at the highest excitation energy the measured temperature can vary from 2 to 20 MeV depending on the thermometer employed. Dynamical effects can be invoked to explain this feature [10,11]; since the system temperature is most likely a time depending variable, the different thermometers may reflect different stages of the reaction, thus making the experimental detection of a liquid-gas phase transition difficult if not impossible.

Here we explore an alternative explanation. In order to study nuclear thermodynamics one needs to be able to univocally associate the detected reaction products with the thermodynamical variables of the decaying source (temperature, density). In other words, a correct modelization of the temperature dependent partition function is needed to reconstruct the deexcitation chain and discriminate between prompt and secondary emission. At low excitation energies this aim is accomplished by the theory of compound nucleus. At higher excitation energies the opening of multifragmentation channels makes an exact evaluation increasingly difficult. Sophisticated Monte Carlo calculations of the multifragmentation pattern are available since many years [2], but the internal partition function at high temperature is poorly known, and the suppression procedure of the state-density integral at high excitation energy is not unique [12–16]. If we limitate our attention to light fragments without states in the continuum, we expect that at high temperature the high lying discrete levels will be increasingly excited. Since most of these states are particle unstable, their population can significantly modify the light particle yields and energy spectra. Feeding from γ -states and side feeding have already been invoked [8,17,18] and quantitatively

ively calculated [19,20] for the Aladin experiment [6] in the attempt of extracting the initial temperature from the measured double ratios. However the results are contradictory and seem strongly influenced by the number of states included in the partition function and the freeze out density employed. The purpose of this paper is to show that if we analyze quasi-complete data and compare different thermometers the parameters of the models can be strongly constrained and the contradictions partially removed.

Side feeding is not the only source of a deformed response of thermometers. Even in the framework of thermodynamical equilibrium, final state interactions in the freeze out configuration can modify the production yields [21]. Here, a modification of the statistical probabilities is proposed, which corresponds to a redefinition of the concept of nuclear freeze out density by means of an excluded volume interaction as in the Van der Waals gas. The correction to the ideal gas approximation is seen to produce sizeable modifications to the nuclear thermometers for finite freeze out densities, by reducing the influence of high lying resonances.

The plan of this paper is as follows: the QSM model [22–25] augmented of a liquid phase in terms of continuum states, and of a first order density correction in the freeze out equation of state is presented in section 2, apparent temperatures are calculated and compared to INDRA[9] data in section 3, and some conclusions are drawn in section 4.

2 Chemical and Thermal Equilibrium Fireball Model

The physical scenario we have in mind is a chemically and thermally equilibrated nuclear source which undergoes a simultaneous disassembly at a fixed temperature T and density ρ . Of course the hypothesis of thermodynamical equilibrium is highly questionable due to the very short reaction times involved in intermediate energy collisions, however this very simple fireball model has been applied with some success since many years to reaction at even higher incident energies (*i.e.* shorter times) [26].

Since we are not interested in an event by event analysis but only in the evaluation of mean values, a simple macrocanonical description can give at least a qualitative estimation of the production yields, and the theoretical formalism has been developed two decades ago [26,22] and frequently exploited since then [23–25,19]. For a number K of different classical non interacting structureless species inside a volume V , the entropy reads

$$S_0 = V \sum_{i=1}^K \frac{g_i}{h^3} \int d^3p n_i(\vec{p}) (1 - \log n_i(\vec{p})) \quad (1)$$

where n_i is the occupation of each energy state and g_i is the degeneracy factor. The free energy is defined as usual as

$$F = E - TS = V \sum_{i=1}^K \frac{g_i}{h^3} \int d^3p \left(E_i + \frac{p^2}{2m_i} \right) n_i(\vec{p}) - TS \quad (2)$$

in which E_i represents the energy of the considered state. Thermal equilibrium in the macrocanonical ensemble implies the definition of a chemical potential as

$$\frac{h^3}{g_i} \frac{\partial F}{\partial n_i} = \mu_i \quad (3)$$

The multiplicity of each species then results

$$M_i = \frac{V g_i}{h^3} \int d^3p n_i(\vec{p}) = \frac{V g_i (m_i T)^{3/2}}{\sqrt{2\pi^2 \hbar^3}} \int_0^\infty dz \sqrt{z} \exp\left(-z + \frac{\mu_i}{T} - \frac{E_i}{T}\right) \quad (4)$$

where the sum runs over the ground state and excited states of the different isotopes. The mass action law of chemical equilibrium implies for the chemical potential of the i -th species

$$\mu_i = \mu_Z Z_i + \mu_N N_i \quad (5)$$

Here, Z_i and N_i are the atomic and neutron number of species i and μ_N (μ_Z) are the neutron (proton) constant chemical potentials, to be determined at any given density to ensure conservation of the total neutron and proton number N, Z

$$N = \sum_{i=1}^K N_i M_i(\mu_i, T) \quad (6)$$

$$Z = \sum_{i=1}^K Z_i M_i(\mu_i, T) \quad (7)$$

The freeze out (or break up) density is calculated by [22]

$$\rho_{FO} = \frac{N + Z}{V_{FO}} = \frac{N + Z}{V + \sum_{i=1}^K V_i M_i} \quad (8)$$

where V_i represents the proper volume of the species i . In this formalism the discrete levels of the different isotopes at an excitation energy E_i^* are treated as independent structureless particles characterized by an internal energy augmented respect to the ground state binding energy B_i as $E_i = B_i + E_i^*$, and their proper degeneracy factor g_i . This corresponds to the implicit assumption that these states are sufficiently narrow, *i.e.* their life time is much longer than the equilibration time, and that density is low enough to make their final state interactions with the nuclear bath negligible. We shall come back to these points later. In this very simple model of a classical gas of non interacting structureless particles for any density, temperature and isospin ratio all the different thermometers (slopes of light particle spectra, double ratios, populations of excited states) give the same, exact, thermodynamical temperature. In the following we shall examine the effect on the apparent temperatures of removing these approximations, namely the effect of quantum statistics, internal structure, and final state interactions.

To take quantum statistics into account, one needs to replace eqs.(1),(4) with

$$S_0 = -V \sum_{i=1}^K \frac{g_i}{h^3} \int d^3p n_i(\vec{p}) \log n_i(\vec{p}) \pm (1 \mp n_i(\vec{p})) \log (1 \mp n_i(\vec{p})) \quad (9)$$

$$M_i = \frac{V g_i (m_i T)^{3/2}}{\sqrt{2} \pi^2 \hbar^3} \int_0^\infty dz \sqrt{z} \left(\exp\left(z - \frac{\mu_i}{T} + \frac{E_i}{T}\right) \pm 1 \right)^{-1} \quad (10)$$

and to add the contribution of the bose condensate [22,23]. In eqs.(9),(10) the upper (lower) sign accounts for Fermi (Bose) statistics. The importance of quantum statistics has been already stressed in refs.[22-24,19]. Here we would just like to

point out the different response of the different thermometers. This is demonstrated in figure 1, where the apparent temperature T_{iso} is plotted as a function of density at a fixed $T = 10$ MeV thermodynamical temperature for different isotopic double ratios and different source masses. The qualitative effect of quantum statistics is to increase the number of bosons respect to the number of fermions [22,24], but we can see that temperatures constructed with heavier isotopes are less perturbed. In particular the $(^{11}\text{C}/^{12}\text{C})/(^{12}\text{C}/^{13}\text{C})$ double ratio, proposed in ref.[27], gives an apparent temperature T_{iso} which is almost insensitive to the break up density. However for reasonably low break up densities the deviations are small for all double ratios and quantum statistics alone cannot explain the difference in the measured T_{iso} [19,9].

A much more important effect is expected to be due to side feeding [20,19]. In this work all known discrete levels of nuclear species with $Z \leq 10$ and width Γ less than a cutoff value Γ_0 are included in the state sum[28], and continuum states are allowed for nuclei of $10 \leq Z \leq 20$ in the form of an effective Fermi gas level density [14]

$$\rho_{FG}(\epsilon) = kA^{-p} \exp(2\sqrt{a(A)\epsilon}) \exp(-\epsilon/T_0(A)) \quad (11)$$

where the parameters are taken from ref.[14] and the limiting temperature T_0 is related for any mass number A to the cut off width Γ_0 by Weisskopf theory through the life time τ of the system

$$\frac{\hbar}{\Gamma_0} = \tau = \frac{C \cdot \exp(b(A)/T_0)}{T_0^2 A^{2/3}} \quad (12)$$

where b is the binding energy per nucleon and C is a constant [29]. Since the life time of the decaying system is for any Γ_0 much shorter than the time of flight towards the detector, the populated excited states are made subsequently decay with the experimentally known branching ratios when available [28], and Weisskopf theory otherwise. The importance of side feeding is immediately evident from inspection of figure 2, that displays the contributions of secondary decay to the α and deuteron spectrum for an initial temperature of 10 MeV and different freeze out densities. At very low densities the light particle slopes are unaffected, however for alpha particle yields the contribution of secondary decay is not negligible even

for densities which correspond to an almost complete vaporization of the system. Such an important contribution necessarily affects also temperatures extracted from double ratios, as it is shown in figure 3 (see also ref.[19,20]). In this figure the same T_{iso} of figure 1 are displayed as a function of the freeze out density, again for an initial temperature of 10 MeV. Since the population of resonances and continuum states is increasingly suppressed for decreasing densities (see figure 2), the initial temperature is approached only in the very low density limit. Moreover, the different isotopic ratios show a different and density dependent response to side feeding. The reduction of the $(^{11}\text{C}/^{12}\text{C})/(^{12}\text{C}/^{13}\text{C})$ T_{iso} respect to the thermodynamical temperature is mainly due to the population of γ -decaying states of the carbon isotopes, while the $(^6\text{Li}/^7\text{Li})/(^3\text{He}/^4\text{He})$ T_{iso} (in the following abbreviated as He/Li) is dominated by α -particle decays from discrete and continuum levels (see fig.2). In the calculation shown in figures 2,3 we have set $\Gamma_0=1$ MeV; the contribution of secondary decays strongly depends on the value of Γ_0 , a higher value giving increased side feeding and reduced apparent temperatures. Figure 4 shows the effect of side feeding on the apparent temperature T_{Li} extracted from the relative population of the ground state and 16.66 MeV excited state of ^5Li . The reduced value of the apparent temperature is due to the increased population of $^5\text{Li}_{gs}$ from the decay of discrete states of ^6Be and ^9B . However temperatures from the relative populations of excited states are less affected by side feeding than isotopic temperatures, and even for the highest break up densities a memory of the initial temperature is kept (compare to the He/Li apparent temperature in figure 3).

Let us now turn to the problem of final state interactions. We have already remarked that in the model proposed above the nuclear gas is completely ideal, *i.e.* the different species are non interacting. For this to be true, the freeze out volume must be considerably larger than the proper volume of the particles. The probability of binary scatterings and reabsorption can be modeled [30] via a single particle Schroedinger equation within a fixed volume for each interacting pair, and the resulting phase shifts enter directly in the internal partition function [26]. However a detailed phase shift analysis is available only for the scattering of very light particles, and a practical implementation of the method suggested in ref.[26] is out of scope here. An alternative method of dealing with collisions and reabsorption at freeze out

is given by an effective excluded volume approach in the spirit of the Van der Waals gas. This method is issued from atomic physics, where it is well known that the partition function diverges if all the states are included in the thermodynamical potential [31]. This artificial divergence comes from the highly unbound excited states which are characterized by orbitals of increasing dimensions and therefore are absorbed by the interaction with neighboring atoms. In an analogous way, the loosely bound particle unstable resonances with a density distribution extending far off the liquid drop mean square radius have to be suppressed from the count of states if the inter-particle distance is smaller than the range of their wave function [26,32].

In the framework of the effective Van Der Waals formalism, the entropy of a non ideal gas at the first order in the density is given by [33]

$$S = S_0 + n \log\left(1 - \frac{b}{V}\right) \quad (13)$$

where S_0 is the ideal gas limit given by equation (9), and b is related to the proper volume of the components through

$$b = \frac{1}{2n} \sum_{i,j}^K M_i M_j (V_i^{1/3} + V_j^{1/3})^3 \quad (14)$$

where n is the total multiplicity and V_i is the proper volume of the i -th species.

The population of each species then gets a density dependent correction

$$M_i = \frac{g_i(m_i T)^{3/2}}{\sqrt{2\pi^2 \hbar^3}} \int_0^\infty dz \sqrt{z} \left(\exp\left(z - \frac{\mu_i}{T} + \frac{E_i}{T} + f_i\right) \pm 1 \right)^{-1} \quad (15)$$

with a suppression factor which is more important the "bigger" the particle is

$$f_i = \frac{n}{V} \frac{\partial b}{\partial M_i} = \sum_{j=1}^K \frac{M_j}{V} (V_i^{1/3} + V_j^{1/3})^3 \quad (16)$$

For the volumes V_i we have taken a spherical shape from the experimental mean square radius for the ground states, and for the resonant structures we have made the hypothesis that the exit channel is preformed in the decaying state [34].

Thus for example the volume of a ${}^8\text{Be}$ will be parametrized as two adjacent alpha particles. Of course this is a very simplistic representation which has to be viewed only as a first attempt to incorporate a mean nuclear interaction in the freeze out configuration.

The effect of the excluded volume interaction is to favour protons, neutrons and alphas over the more loosely bound structures like deuterons and high lying resonances. This is shown in figure 5a, which displays the suppression factor $s_i = \exp(f_i)$ of eq.(16) for deuterons and ${}^8\text{Be}$ normalized to the s_p of a proton as a function of the break up density. One can see that the source is behaving as an ideal gas only in the limit of vanishing density. The effect on the double ratio apparent temperatures, shown in figure 5b for the same T_{iso} as in figures 1 and 3 above, is to decrease the effect of side feeding at high density and to improve the linearity of the response with respect to the initial temperature. Some evidences that a final state interaction may indeed be important in the definition of the freeze out configuration can be inferred by looking at production yields of light particles. Figure 6 shows the relative multiplicity of light charged particles as a function of excitation energy with (upper part) and without (lower part) final state interaction, compared to experimental data of quasi-projectile vaporization events in the reaction $\text{Ar} + \text{Ni}$ at 95 MeV/u [35]. In both calculations the freeze out density has been fixed to one third of the saturation density. Another calculation with this model for the same system was presented in ref.[35], but only a limited number of resonances was included. In the ideal gas case, the experimental proton over deuteron ratio can be fitted only by imposing a freeze out density so low that the proton over alpha ratio is overestimated by more than an order of magnitude, as it is shown in figure 7. In these calculations as in the following ones the (average) excitation energy is univocally defined for any input temperature and density as

$$E^* = \langle E \rangle - B_s = \sum_i M_i(T_i + B_i + V_i) - B_s \quad (17)$$

where T_i is the average kinetic energy of the i -th species, V_i is the average inter-particle Coulomb energy assumed independent of the freeze out configuration [36], and B_s is the binding energy of the source. The model calculation including the

excluded volume interaction reproduces reasonably well also the energy spectra of the emitted particles in the whole $10 \leq E^*/A \leq 25$ excitation energy range [35]. The calculations of the following section will be performed with the final state interaction eq.(15), unless differently specified.

3 Comparison to Experimental Data

We have seen in the preceding section that all the corrections we have introduced to the model represented by equation (1) are strongly density dependent. Therefore a knowledge of the freeze out density is indispensable if we want to quantitatively calculate the response of the different thermometers [20,19]. It is however interesting to notice that the influence of the density is strongly reduced when the apparent temperatures are plotted, as in the experiments, as a function of excitation energy (defined in the model by eq.(17)). This is shown for the *He/Li* thermometer in figure 8, and the qualitative result is independent on the double ratio, mass of the decaying source, and cut-off Γ_0 employed. This means that, as far as T_{iso} are concerned, a large deviation between calculation and data cannot be attributed to an imperfect evaluation of the freeze out density, and must reflect a break down of the hypothesis of the model. Therefore a comparison to experimental data can be used as a test of the strong hypothesis of thermal and chemical equilibrium. On the other side, since a whole bunch of initial temperatures can produce the same experimentally measured double ratio, we can already conclude that these thermometers are not best suited to measure the thermodynamical temperature [20], and the 'primordial' caloric curve which we shall extract will be subject to important uncertainties.

In this paper we shall concentrate on the analysis of the deexcitation of the projectile in *Ar + Ni* collisions at 95 MeV/u bombarding energy, measured by the INDRA collaboration [9]. The comparison to the data of refs.[6,7] is in progress [37]. As it is stressed in ref.[20], it is very important to fix the parameters of the model in order to reproduce the experimental mass distribution, a too steep distribution resulting in an underprediction of secondary feeding corrections. We have therefore chosen to fix the freeze out density in order to reproduce, at any temperature, the

experimental ratio Z_{LCP}/Z_{tot} between the charge stored in light charged particles ($Z \leq 2$) and the total source charge, which is a direct measure of the observed vapour over liquid population. The liquid over vapour fraction is itself linked, through the value of the chemical potential, to the freeze out density. The clear correlation of this variable to the freeze out density is demonstrated in figure 9 for a mass $A = 36$ system. Non crossing and smoothly varying isothermal lines are obtained by varying the break up density over a wide range, thus allowing to associate to any excitation energy an unique value of temperature and chemical potential. Figure 10 displays the result of the calculation with the excluded volume interaction for the different double ratios T_{iso} and the deuteron slope measured in the experiment [9]. All the apparent temperatures are reasonably well reproduced, thus suggesting that collective effects play a minor role and thermodynamical equilibrium may actually have been reached in this reaction. The initial temperature is, for all excitation energies higher than 10 MeV, very close to the deuteron slope parameter, while all the temperatures extracted from double ratios have important feeding corrections. In the context of this model the slope parameter thus seems the most accurate thermometer. A word of caution is however necessary because of the insensitivity of the double ratio thermometers to the freeze out density (see figure 8). The uncertainty in the parametrization of the continuum level density and of the volume of excited states, and the approximate average treatment of Coulomb energies causes an uncertainty in the determination of the chemical potential, and consequently on the relation between the initial temperature and the excitation energy, which is difficult to quantitatively assess. Another calculation with this model for the same system was presented in ref.[9], where however continuum states were neglected. The main effect of including continuum states is to improve the agreement with the data for low excitation energy. The measured excitation energy dependence of the proton over alpha ratio, used in our previous work [9] to fix the freeze out density, is still properly accounted for, for excitation energies greater than 10 MeV/u. In this calculation continuum states are allowed for fragments of atomic number $Z \geq Z_0 = 10$. Only a very slight difference is observed if Z_0 is lowered to $Z_0 = 6$. This is a specific feature of small systems (here $A=36$) at high excitation energies. For heavier mass and/or lower temperatures the influence of the continuum is non

negligeable and a more sophisticated calculation of the level density is needed. The influence of the life time parameter Γ_0 is shown in figure 11. The slope parameter is unaffected while the *He/Li* isotopic temperature is decreased by increasing the number of resonances allowed in the calculation. However we can see that for life times $\tau \leq 100 \text{ fm/c}$ ($\Gamma_0 \geq 2$) the result is not strongly dependent on this parameter, due to the resonance suppression effect of the excluded volume interaction. As it was observed in ref.[9], for excitation energies lower than approximately 10 MeV per nucleon, the experimental apparent temperature extracted from deuteron slopes are compatible with a Fermi gas energy/temperature relation with a density level parameter $a = 10$. Neither in the data nor in the calculation a plateau is observed, but the failure of the model at low excitation energies suggests that we are facing a transition between an evaporative regime characterized by a Fermi gas density of states, and a multifragmentation one where the system can be described as a gas of loosely interacting nuclear species in thermodynamical equilibrium. In the context of the Berlin model [38], such a behaviour is characteristic of a first order phase transition. The linear relationship between excitation energy and temperature has not to be interpreted as a complete vaporization of the system into free nucleons with the classical maxwellian dependence $E^* = 3T/2$. This is shown in figure 12, which displays the different contributions to the excitation energy: the overall behaviour is dominated by the (linearly varying) kinetic energy, but even at the highest temperatures bound particles contribute in a non negligible way to the energy balance of the system. The coulomb energy is approximately constant here since the freeze out density turns out to vary very slightly with temperature. If speaking of a gas phase may be appropriate, one has to bear in mind that the nuclear gas keeps a composite structure even at temperatures higher than the critical temperature.

The effect of neglecting the correction to the ideal gas situation is dramatic, as it is shown in figures 12 and 13. The experimentally observed difference between the isotopic thermometers is not reproduced, and the net effect of side feeding is augmented. Since most of the resonances have an important branching ratio to alpha particle decay, in the ideal gas case side feeding effects are probably overestimated. The deuteron slope is also highly overestimated, but this result may be partly due to an incorrect evaluation of the freeze out density. Let us finally turn to the temperat-

ure determination from the relative population of excited states. Figure 14 shows, as a function of excitation energy, the temperature T_{Li} extracted from the 5Li ground state and excited state population, together with the isotopic $(d/t)/({}^3He/{}^4He)$ T_{iso} for the particular class of vaporization events of the same $Ar + Ni$ reaction [9,35]. If in the ideal gas scenario we relax the vaporization condition $Z \leq 2$ for the reaction products, T_{Li} lowers to the dashed curve in the upper panel of figure 14. In any case, the value of this temperature is much higher than typically measured values of T_{Li} [4]. The experimental evaluation of T_{Li} for these events is currently in progress [39]. Of course the numerical value of this temperature in the calculation with final interaction is strongly dependent on the shape assumed for the discrete excited states. Here we just want to stress the qualitative idea that the low temperatures systematically extracted from excited state populations may be due to the suppression of the more loosely bound structures via a finite state interaction.

4 Conclusions

In this paper we have presented an extended QSM model [26,23] which includes side feeding from continuum states and a schematic final state excluded volume interaction. We have focussed our attention on the determination of nuclear temperature via different thermometers based on double ratios of neighbour isotopes, relative population of excited states, and slopes of light particle spectra. We have demonstrated that the hypothesis of thermodynamical equilibrium is compatible with the experimental measurement of different temperatures using different thermometers [9]. We have analyzed in detail the different origins of the biased response of the thermometers, side feeding and final state interactions playing a leading role. The model fails to reproduce the $Ar + Ni$ data at 95 MeV/u [9] for excitation energies lower than approximatively 10 MeV/u, thus showing a clear transition from an evaporative regime to a multifragmentation one. For the high excitation energies, a linear slope $dE^*/dT = 1.5$ is observed which however is not the signature of a complete vaporization of the source but is the result of a complicated interplay between kinetic energies of emitted fragments, electrostatic potential at freeze out,

and reaction Q -value. In this regime, the data can be fairly well reproduced by the scenario of a quantum weakly interacting gas of nuclear species in thermodynamical equilibrium. A quantitative extraction of a nuclear caloric curve is still problematic due to the relative insensitivity of the He/Li isotopic ratio to the initial temperature. However, the slope of deuteron spectra seems an interesting candidate for the high energy branch of the caloric curve.

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Figure captions

Figure 1 : Calculated apparent temperature from double ratios of neighbour isotopes [5] as a function of the freeze out density. The thermodynamical temperature is 10 MeV. Quantum statistics has been taken into account. The mass number of the decaying source is $A = 100$ (upper panel) and $A = 50$ (lower panel).

Squares: $(^{11}C/^{12}C)/(^{12}C/^{13}C)$

Circles: $(^6Li/^7Li)/(^3He/^4He)$

Triangles: $(d/t)/(^3He/^4He)$

Figure 2: Energy spectrum of α -particles (2a,2c) and deuterons (2b,2d) for a break up temperature of 10 MeV and a break up density $\rho_{FO} = \rho_0/2$ (2a,2b) and $\rho_{FO} = \rho_0/10$ (2c,2d).

Dashed lines: primary yield.

Dotted lines: evaporation from continuum states

Dashed dotted lines: secondary decay of discrete resonances

Full lines: total spectrum.

On each panel, the slope parameter obtained from a Maxwell fit of the total spectrum is shown.

Figure 3: As figure 1, but side feeding from discrete (up to a maximum width $\Gamma_0 = 1$ MeV) and continuum excited states is included.

Dashed line: He/Li apparent temperature for an initial temperature $T = 20$ MeV.

Figure 4: Apparent temperature extracted from the relative population of the ground state and excited state at $E^* = 16.66$ MeV of 5Li as a function of the freeze out density. Two different temperatures are shown. Side feeding has been included taking into account all tabulated discrete excited states contributing to 5Li yield.

Figure 5: Upper part: suppression factor (see text) for deuterons (full line) and 8Be (dashed line) as a function of the freeze out density for a fixed $T = 10$ MeV temperature. Lower part: like figure 3 above, but with inclusion of a final state interaction.

Figure 6: Relative multiplicity of light charged particles as a function of excitation energy for vaporization events in the quasi-projectile deexcitation from the reaction $Ar + Ni$ at 95 MeV/u. Symbols: experimental data from ref.[35]. Lines: calculation with (upper panel) and without (lower panel) final state interaction.

Figure 7: Symbols: measured proton over α (6a,squares) and proton over deuterons (6b,triangles) yields from ref.[35] as a function of the excitation energy per nucleon. Lines: model calculation without final state interaction and freeze out density fixed to one third (full lines) or one tenth (dashed lines) of the saturation density.

Figure 8: He/Li isotopic apparent temperature as a function of the thermodynamical temperature (left side) and the excitation energy per nucleon (right side) at three different freeze out densities for a decaying mass $A = 50$ and a cut-off width $\Gamma_0 = 1$ MeV.

Figure 9: Isothermal lines in the Z_{LCP}/Z_{tot} versus excitation energy plane for a decaying source with a mass $A = 36$. Increasing density goes in the direction of

decreasing energy. Dashed lines and symbol: example of the method of extracting a temperature and density from an (hypothetical) experimental point.

Figure 10: Apparent temperature as a function of excitation energy per nucleon extracted from deuteron slopes (upper triangles) and different isotopic double ratios. Full lines: this model for a decaying $A = 36$ source and $\Gamma_0 = 2$ MeV. Dashed line: thermodynamical temperature used in the calculation. Symbols: experimental data from ref.[9]. Circles: $({}^6\text{Li}/{}^7\text{Li})/({}^3\text{He}/{}^4\text{He})$
Stars: $(d/t)/({}^3\text{He}/{}^4\text{He})$
Squares: $(p/d)/({}^3\text{He}/{}^4\text{He})$
Triangles: $(p/d)/({}^6\text{Li}/{}^7\text{Li})$

Figure 11: Effect of the cut-off parameter Γ_0 on the apparent temperatures from deuteron spectra (upper lines) and He/Li T_{iso} (lower lines) compared to the experimental data of ref.[9]. Triangles: experimental slope of deuteron spectra. Circles: T_{iso} from the measured $({}^6\text{Li}/{}^7\text{Li})/({}^3\text{He}/{}^4\text{He})$ double ratio. Dashed dotted line: Fermi gas $T = \sqrt{10E^*}$ caloric curve.

Figure 12: Different contributions to the excitation energy as a function of the thermodynamical temperature in the calculation of figure 10 above. Full line: total excitation energy. Dashed line: kinetic energy. Dotted line: binding energy. Dashed dotted line: coulomb energy.

Figure 13: As figure 10 above, but without final state interaction and $\Gamma_0 = 1$ MeV.

Figure 14: As figure 11 above, but without final state interaction.

Figure 15: Apparent temperature extracted from the isotopic double ratio $(d/t)/({}^3\text{He}/{}^4\text{He})$ (curves labelled T_{iso}) and population of excited states of ${}^5\text{Li}$ (curves labelled T_{Li}) as a function of the excitation energy per nucleon, for vaporized quasi-projectiles ($Z \leq 2$) in the $\text{Ar} + \text{Ni}$ reaction at 95 MeV/u. Upper panel: ideal gas. Lower panel: final state interaction. Symbols: experimental data for T_{iso} from ref.[9,35].

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Figure 1

Figure 2

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Figure 10

Figure 11

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Figure 13

Figure 14

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