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Abstract:

We reconsider the possibility of deducing the entropy attained in energetic heavy ion reactions by means of the measured abundances of compounds. In-medium corrections for the effective binding forces are seen to sensitively influence the balance between nucleons and compounds. They reduce the deuteron production to rates close to the observed values with entropy values in line with conventional expectations.

DEUTERON PRODUCTION - AN ENTROPY PUZZLE?

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Recently Siemens and Kapusta [1] suggested a calibration of the entropy attained during the hot phase of a relativistic heavy ion collision by means of the observed deuteron abundancies. Their reasoning bases on the following two assumptions:

- i) the entropy per nucleon s (ignoring the entropy content of pionic degrees) can be calculated by the free fermion-gas law

$$s = 5/2 - \ln(\rho\Lambda^3/4), \quad (1)$$

where ρ is the matter density of nucleons, and $\Lambda = (2\pi\hbar^2/mT)^{1/2}$ is the thermal wave length of the constituents (nucleons) of the system at temperature T ;

- ii) at the late stage of the reaction the ratio of deuterons to protons follows from the law of mass action

$$\rho_d/(\rho_p\rho_n) = (3/2)\Lambda^3 \exp(-E_d/T) \rightarrow E_d \ll T \quad (2)$$

Thus, in the limit of temperatures large compared to the chemical potential of the deuterons E_d the one body properties required in (1) can be inferred directly from the observed ratio of deuterons to protons (omitting heavier compounds) $R_{dp} = \rho_d/\rho_p$

$$s = 5/2 - \ln(R_{dp}/3/2) - 1.25 R_{dp}/(1+R_{dp}) \\ = 3.945 - \ln R_{dp} \quad \text{if } R_{dp} \ll 1. \quad (3)$$

Employing these two assumptions values of 5.0 to 6.0 units in entropy per baryon are deduced from the variety of data covering the range from 0.4 to 2.1 GeV/nucleon beam energy [2]. These values exceed by about two units or more the expectations from conventional reaction models, like the intra-nuclear cascade [3] or by hydrodynamic models with non exotic equations of state.

According to the authors of ref. [1], one possible explanation out of this puzzle could be the release of new degrees of freedom during the reaction (e.g. dissociation into quarks). However, the discrepancies even grow towards lower bombarding energies, where such new degrees of freedom evidently play a minor role.

In this note we like to draw attention to the following two facts: within the range of application the *free Fermion gas* assumption (i) is still justified while the *law of mass action* (ii) may meet serious difficulties.

In fact, recent variational calculations of nuclear matter at finite temperatures by Friedman and Pandharipande [4] show entropies, fig. 1, that are in close agreement with those obtained from eq. (1). The actual deviations do not exceed 0.1 units in entropy.

Rather, we like to discuss the *law of mass action* critically. Although we are fully aware of the problem to employ static equilibrium concepts, that is to say to ignore relaxation phenomena, we like to discuss this limit for the time being in the sense of an estimate for the most probable state the system likes to attain. In brevity, we think of a freeze-out concept [5] (as also employed in ref. [1]) where a static detailed balance determines the production rates of compounds. Nevertheless, already within this picture we do see facts that lead to significant corrections of the ordinary balance eq. (2).

Indeed, given the picture of a chemical equilibrium [5] between nucleons and deuterons, eq. (2) holds only in the low density regime, where the compounds move relatively freely except for occasional chemical reactions. In denser systems the proximity of the surrounding matter alters the effective binding forces of the compounds to such an extent that the bound states merge the continuum. The density beyond which bound compounds at rest do no longer occur is called the *Mott density* [6] $\rho_{\text{Mott}}(P=0)$, in analogy to similar phenomena in dense plasma [7]. Compounds that move with high velocity relative to the surrounding matter are less degraded, since the quenching essentially results from *Pauli blocking*. At even higher densities where the averaged spacing between the constituents becomes comparable or even less than the size of free compounds the notion of compounds in chemical equilib-

rium makes no sense anymore. Rather, correlations [3] are then the proper object to study.

Our objective here is to draw attention to the in-medium corrections to the binding forces which are relevant in the intermediate density regime. The respective energy shift of the deuteron binding energy (and other compounds) in the surrounding nuclear matter at density and temperature p and T is calculated within the *ladder Hartree-Fock* approximation [6], later referred to as *quantum statistical* methode (QS). For details we refer to ref. [6].

It is illustrative, though, to consider some simplifications that lead to analytic expressions. This is given in the low density limit where the whole correction appears as a shift of the chemical potential proportional to the density

$$p_d/(p p_n) = (3/\sqrt{2})\Lambda^3 \exp\{-(E_d + \delta_{P_{d=0}}^{\text{Pauli}} p)/T\}. \quad (4)$$

Although the deuteron chemical potential $E_d = -2.2 \text{ MeV}$ is by an order of magnitude smaller than the temperatures discussed, already small corrections may sensitively influence the balance.

For the simple case where i) all deuterons are at rest with respect to the surrounding nuclear medium ($P_d=0$), ii) the deuteron wave functions are of Gaussian form, iii) the nucleon-nucleon interaction is of Skyrme type, and iv) the momentum distribution of the nucleons follows a Maxwell Boltzmann law the additional shift to the unperturbed binding energy E_d can be obtained in closed form

$$\delta_{P_{d=0}}^{\text{Pauli}} = 2.33 \cdot 10^3 / \{1+T/(2|E_d|)\}^{3/2} \text{ MeV fm}^3 \quad (5)$$

The additional density and temperature dependence of the energy shift has the effect that deuterons with $P_d=0$ do exist only in well confined parts of the (p,T) plane, namely as long as the chemical potential remains negative, i.e. for all $p < p_{\text{Mott}}(P_d=0) = |E_d|/\delta_{P_{d=0}}^{\text{Pauli}}$.

Thermal motion of the deuterons reduces the strong quenching predicted by eq.s(4,5). However, the result can no longer be expressed in such a close form. Fig. 2 shows the resulting abundances of all compounds up to mass 4 for the range of matter densities below the normal nuclear stability. This calculation uses Bose Einstein distributions for the deuteron momenta P_d and Fermi Dirac distributions for the nucleon momenta rather than the Maxwell Boltzmann form used for the estimate (5). The dashed lines show the predictions of the ordinary law of mass action (2). The full lines represent the quantum statistical treatment which includes the in-medium corrections for a system of nucleons and all stable compounds up to mass 4. Note that relative to the deuterons the Mott transitions of the heavy compounds appears at higher densities. While the simple law (2) predicts a copious production of deuterons at densities close to p_0 , the improved law shows the strong influence of the Pauli quenching, which for $T = 40 \text{ MeV}$ allows for a production rate of $R_{dp} \approx 0.3$ at most for p around $0.3p_0$. Note, that this value is already in close agreement with the experimentally rate of 0.31 ± 0.01 observed at 400 MeV/nuc.l. beam energies in the Ar+KCl system. Due to the discussed saturation actually a whole range of freeze-out densities from 0.2 to $1.0 p_0$ can cope with the data. Applying formula (1) one infers entropy values that range from $s = 4.5$ for a dilute freeze-out down to $s = 2.9$ for a freeze-out at nuclear matter density. The last value, however is fully in line with conventional expectations which handle values of $s = 3 \pm .3$ at 400 MeV/nuc.l. [1,11]. The temperatures required in the above analysis have been inferred from the slopes of the observed inclusive proton and deuteron spectra ($T = 40 \text{ MeV}$ corresponds to a beam energy of about 400 MeV/nuc.l.).

In view of the above considerations the entropy puzzle discussed by Siemens and Kapusta [1] appears less embarrassing. There are in fact many mechanisms that may influence the deuteron rates, like: final state decay of meta stable compounds [8]; dynamical quenching effects either through an excluded volume [9], or through the in-medium corrections of the binding forces as discussed here, or ultimately relaxation phenomena that question the use of static equilibrium concepts.

Therefore the entropy deduced from the d/p ratio is seen to be highly model dependent. This may also turn out for the counting of nucleon and deuteron like objects (correlations) that are contained in compounds of heav-

ier mass as introduced by Bertsch and Cugnon [3] and reconsidered in ref [10]. Although suggestively presented in ref. [1], we see no possibility of an absolute calibration of the entropy by means of abundance measurements, since already for the static balance in-medium corrections do already seriously effect the equilibrium rates. How can we discard similar influences for the dynamical process in concern?

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Figure Captions

Figure 1) The entropy as obtained in ref.[4] by a variational calculation of nuclear matter at finite temperature ($T = 20$ MeV), full line, compared to the free fermi gas result, eq.(1), dashed line.

Figure 2) Percentage of protons appearing as free protons, or bound into deuterons or all other compounds up to mass 4 as a function of the freeze-out density ρ . Dashed lines: the ordinary law of mass action (eq.(2)); full lines: the quantum statistical treatment with the in-medium corrections dis-

cussed. The arrows give the Mott densities for deuterons and compounds of mass 3, if the compounds are at rest relative to the surrounding nuclear medium at temperature T .