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VOLUME CORRECTIONS FOR THE SPECIFIC ENTROPY IN NUCLEON-DEUTERON MIXTURES

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ABSTRACT

Some estimations are made for the influence of the deuteron volume on the d/p ratio in dilute, hot deuteron-nucleon gases. The result is that in reasonable equations of state this volume can imitate an "entropy excess" similar to that in 0.4-0.8 GeV/nucleon heavy ion collisions, so it is possible that there is no excess at all.

АННОТАЦИЯ

Дается оценка влияния объема дейтрона на число дейтронов в горячем жидком газе дейтронов и нуклонов. Результат показывает, что обычно этот объем имитирует "избыток энтропии", который подобен наблюдаемому при столкновениях тяжелых ионов при энергии 0,4-0,8 ГэВ/нуклон, таким образом, доказательства существования этого "избытка энтропии" недостаточные.

KIVONAT

Megbecsüljük a deuterontérfogat hatását a d/p arányra híg forró deuteron-nukleon gázban. Az adódik, hogy általában e térfogat egy "entrópiatöbbletet" imitál, amely hasonló a 0,4-0,8 GeV/nukleon energiáju nehézionütközésekben találthoz, igy lehetséges, hogy nincs is ilyen többlet.

1. INTRODUCTION

The observed d/p ratio in heavy ion collisions of 400-800 MeV/nucleon beam energy is definitely lower than the theoretical value predicted by ideal gas models [1]. One interpretation is that there is an "entropy excess" in the process, some $\Delta\sigma \approx 2$ extra specific entropy production could explain the low d/p ratio [1], [2]. Such an extra entropy production would be possible e.g. in inequilibrium phase transitions [3], however nucleon-quark phase transtion cannot be expected at these beam energies [4],[5]. Nevertheless, it is not obvious that the d/p ratio is the proper way to measure the entropy, since the deuteron is an extended system. In fact, using the familiar van der Waals equation of state, a 10 fm^3 deuteron volume can explain the low deuteron ratio [2]. Since the van der Waals equation of state is phenomenological, its relevance would need some further discussion. Thus here we show that any reasonable equation of state (if not ideal) would lead to the same order of magnitude for the entropy correction.

2. THE EQUATION OF STATE

It is convenient to use the baryon density n, deuteron concentration c and specific entropy σ as characteristic quantities. They are defined as follows:

$$\begin{aligned} n &= n_n + 2n_d \\ c &= n_d/(n_n + 2n_d) \\ \sigma &= s/(n_n + 2n_d) \end{aligned} \qquad (2.1)$$

where s is the entropy density, while n_n and n_d stand for the nucleon and deuteron number densities, respectively. In adiabatic processes (as the expansion of fireclouds, approximately) σ is constant. In the ideal gas limit

$$\begin{aligned} p &= (n_n + n_d)T \\ \varepsilon &= \frac{3}{2}(n_n + n_d)T \end{aligned} \tag{2.2}$$

whence the ideal equation of state is

$$\varepsilon_{id} = q(c)(1-c)^{5/3} n^{5/3} e^{\frac{2}{3}\frac{\sigma}{1-c}} \tag{2.3}$$

The function q(c) cannot be determined from the phenomenologic laws (2.2), but it can be calculated e.g. for a mixture of non--interacting Boltzmann gases [1]. Then in chemical equilibrium [1],[6]

$$\sigma = 3.95 - \ln 2 - \ln c + \ln(1-2c) - 5c/2 \tag{2.4}$$

For thin nonideal gases one can write

$$\begin{aligned} \varepsilon &\doteq \varepsilon_{id}[1 + \eta(\sigma,n,c)] \\ |\eta| &\ll 1 \end{aligned} \tag{2.5}$$

Now, as an approximation, we assume that a pure nucleon gas is ideal, and the deviations from the ideal behaviour come from the deuterons (at densities produced in collisions of several hundred MeV beam energies this seems to be correct). Then

$$\lim_{c\to 0} \eta(\sigma,n,c) = 0 \tag{2.6}$$

3. THE CHEMICAL EQUILIBRIUM

There are $d \rightleftharpoons 2n$ transitions in the system. In this process the condition for chemical equilibrium is

$$2\mu_n - \mu_d = 0 \tag{3.1}$$

where μ denotes the chemical potential. Using the canonical variables s, n_n and n_d,

$$T = \frac{\partial \varepsilon}{\partial s}$$
$$\mu_i = \frac{\partial \varepsilon}{\partial n_i} \tag{3.2}$$

Then Cond. (3.1) can be written as

$$\left(\frac{\partial \varepsilon}{\partial c}\right)_{eq} = 0 \tag{3.3}$$

whence, using eq. (2.5)

$$\frac{\eta_{,c}}{1+\eta} + \frac{q_{,c}}{q} - \frac{5}{3}\frac{1}{1-c} + \frac{2}{3}\frac{\sigma}{(1-c)^2} = 0 \tag{3.4}$$

This equation shows that, measuring the deuteron concentration c, the interaction terms imitate an "excess" in the specific entropy

$$\Delta\sigma = \frac{3}{2}(1-c)^2\frac{\eta_{,c}}{1+\eta} \tag{3.5}$$

that is, at the same concentration the specific entropy of the interacting mixture differs by $\Delta\sigma$ from the value calculated from ideal models.

4. THE DILUTE GAS LIMIT

The evaluation of eq. (3.5) would need the acutal from of η, but the interaction term in the equation of state is very poorly known for nucleon-deuteron mixtures. In principle this equation offers a possibility to measure η by comparing the calculated entropy production to the measured d/p ratio, but this is definitely not the goal of this paper. Here we want to make decent estimations for $\Delta\sigma$ without specifying the model. Obviously, this cannot be done for the generic case; however, it is possible in the dilute limit, as we shall immediately see. This seems to be sufficient in the investigated case, because at 0.4-0.8 GeV/nucleon beam energy the observed d/p ratio was cca. 0.1 [1], and the expected maximal density is not higher than three normal nuclear density [7]. Therefore now we restrict ourselves to the limit $c \to 0$, $n \to 0$, and, from technical reasons, assume that η can be expanded into Taylor series in n as well as in c at 0. Furthermore, from physical considerations, and according to eq. (2.5), we require that the mixture go to an ideal one when $n \to 0$.

Since η is dimensionless, as well as σ and c, it has to contain volume parameters from dimensional reasons. Eq. (2.6) indicates that these parameters belong to the deuterons, and here, for simplicity's sake, we use a single parameter V.

From the above assumptions, in the dilute limit η has the form

$$\eta(\sigma,n,c) = k(\sigma)nVc + \text{(higher terms)} \tag{4.1}$$

Then the leading term in $\Delta\sigma$ is

$$\Delta\sigma = \frac{3}{2}\,k(\sigma)nV \tag{4.2}$$

Note that the deuteron volume is multiplied by the total baryon density, so this term survives in the $c \to 0$ limit.

The evaluation of eq. (4.2) is not possible without taking $k(\sigma)$ from specific models. If one does not want to do this, only estimations can be done. The sign of k is positive if the states containing greater part of the nucleons in deuterons are energetically dispreferred by the nonideal term η from any reason, which seems to be more probable than the opposite case (note that in the investigated cases the deuteron binding energy is negligible compared to the temperature). Since $k(\sigma)$ is a dimensionless function of a dimensionless variable, and in the investigated collisions σ is in the order of 1 [1],[6], by means of Dirac's principle about the natural form of physical laws one can conclude that k is expected in the order of 1 too. Although specially chosen models may quite well produce a definitely lower value for k, in the present state of knowledge about the equation of state a low value would seem to be forced, and the phenomenologic van der Waals equation of state yields $k = +2/3$, in accordance with our estimation. In any case, if the nonideal part of the equation of state is unknown, eq. (4.2) can be interpreted that the specific entropy of the hot, compressed stage can be calculated from the observed d/p ratio only with an error $\delta\sigma \approx nV$.

Identifying V with the geometric volume calculated from the deuteron breakup cross section, or with volumes of reasonable wave functions, $V \approx 10\ fm^3$, or slightly greater [8]. But then $\Delta\sigma \approx 3$ at $2n_0$ density, which is quite enough to eliminate the "measured" entropy excess.

4. CONCLUSIONS

We have estimated the influence of the deuteron volume on the d/p ratio in a dilute hot deuteron-nucleon mixture. The result is that, if all the unknown dimensionless parameters of the unknown equation of state are in the order of 1, then the deuteron volume imitates an excess of the specific entropy of order nV, and this value is similar to the observed "entropy excess" in heavy ion collisions at 0.4-0.8 GeV/nucleon beam energy. This result is confirmed by the model calculation with a van der Waals equation of state. Although the relevance of this equation of state has not been proven here, the old phenomenologic van der Waals equation was definitely not constructed for explaining these reactions, so it is a good representative of unspecified equations of state. In any case, our conclusion is that the specific entropy calculated from the final d/p ratio carries an error of order nV, if the nonideal part of the equation of state is unknown, and using reasonable deuteron volumes, this error is in the order of the "measured" excess, so there is no clear evidence for an excess at all.

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