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ENTROPY DETERMINATION FROM FRAGMENT YIELDS
IN HIGH MULTIPLICITY HEAVY ION COLLISIONS

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Entropy Determination from Fragment Yields in High Multiplicity Heavy Ion Collisions

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Entropy is created in heavy ion collisions predominantly in the initial high density phase of the reaction and may yield information on this stage. The problem of measuring the entropy per nucleon S/A produced in heavy-ion reactions was first tackled by Siemens and Kapusta[1]. They claimed that measuring the ratio of the deuteron yield to the proton yield R_{dp} is sufficient to determine the entropy from the data via the simple formula:

$$S/A = 3.95 - \ln R_{dp}$$

Their treatment was subsequently extended[2,3] to include tritium, ^{3}He and α-particles by defining the ratio d-like - to - p-like

$$\tilde{R}_{dp} = \frac{d + \frac{3}{2}\ (t + {}^3He) + 3\ {}^4He}{p + d + t + 2\ ({}^3He + {}^4He)}$$

It was claimed[2] that by inserting $\tilde{R}$ instead of R into eq. 1 , the effects of the formation of clusters other than the deuteron are readily included, and the modified eq. 1 can be used to extract the entropy from data.

It was pointed out[4], however, as early as 1981 that the decay of particle instable complex fragments (d^*, He^*, Li^* etc.) can alter the values of R_{dp} and $\tilde{R}_{dp}$ considerably: decay protons (and neutrons) are abundantly produced in an evaporation stage subsequent to the thermal and chemical break-up. They spoil the entropy determination via the simple formula, eq. 1, and require the numerical evaluation of the relation $S(\tilde{R}_{dp})$, e.g. via a quantum statistical model of fragment formation, which includes the decay of instable fragments[4].

In all these models it is assumed that chemical and thermal equilibrium is achieved in the high density stage and not lost during the following expansion of the hot, dense piece of participant nuclear matter. As the break-up density and temperature are reached, the interactions between the nuclear fragments cease. The fragment yields should be altered afterwards only by the decay of the particle-instable states. From the fragment yields one can calculate S/A in the moment of break-up which is, if the assumption of isentropic expansion is correct, a signal from the high-density stage of the reaction.

The present quantum statistical model calculation is based on ref. 4: we assume thermal and chemical equilibrium in the break-up moment of the nuclear medium. We have included ~40 stable and ~500 instable light

nuclei[6] up to mass number 20. The yield of each species is determined from its chemical potential, its statistical weight and the temperature via Bose- or Fermi-distributions. The chemical potentials of clusters in equilibrium are given by the chemical potentials of the constituents and the binding energy E_i[5]:

$$\mu_i = Z_i \mu_p + N_i \mu_n + E_i$$

with

$$E_i = Z_i m_p c^2 + N_i m_u c^2 - m_i c^2 \quad .$$

μ , m are the chemical potentials of protons and neutrons, respectively. They are adjusted to give the correct N/Z ratio of the participant-zone and the desired break-up density. Excluded volume effects are taken into account via

$$\rho = \frac{\rho_{pp}}{1 + \frac{\rho_{pp}}{\rho_0}}$$

where ρ_{pp} is the point-particle density.
The entropy is given by

$$S = \sum_i \left(\frac{5}{3} U_i - \mu_i n_i\right)/T$$

where U_i is the thermal energy and n_i is the abundance of each species and the sum runs over all species.

For the sequential decay of excited fragments after the break-up we make use of the tables of Ajzenberg-Selove[6]. Here we also find the statistical weights and binding energies for each species. To determine which

level of the daughter-nucleus is populated by a specific decay we derived the transition probability composed of a barrier-penetrability factor and the density of final states in the system daughter-nucleus plus the emitted particle.

The main difference between the present model and the one mentioned above[1,2,3] is the inclusion of heavier and instable fragments and binding energies into our calculations, while the approach of ref.[1-3] stops at the α-particle, excludes instable fragments and sets

$$\mu_i = (Z_i + N_i)\ \mu_N ,$$

where μ_N is the nucleon chemical potential. Furthermore, it is assumed in refs. 1-3 that protons are much more abundand in the chemical equilibrium stage than all clusters together, an approximation which is not supported by recent data[10]. Only under this assumption is it possible to derive the simple formula, eq. 1, for the entropy. Both models assume an infinite system.

What are the results of the present model calculation? In figure 1 we show the behaviour of the system at constant entropy. Note the remarkable difference to the simple $\rho^{2/3}$ dependence of the temperature expected from a pure nucleonic gas without the possibility of fragment formation. Mass distributions for different temperatures are shown in figure 2. We recognise the big influence of the binding energies at low temperatures. In particular note that the mass yields are rising with increasing mass at T=2 MeV.

In figure 3 we present two observables, namely the total multiplicity and $\tilde{R}_{dp}$, which can be used to determine the entropy S/A from experiment, since their entropy-dependence is not much changed by a variation in the unknown break-up density.

The multiplicity of heavy fragments is a good tool to measure entropies around 1.5<SA<3 while the d_{like}-to-p_{like}-ratio gives information about the entropy for larger S/A values. Nonetheless, the relation between S/A and the d_{like}/p_{like}-ratio is not as simple as suggested earlier[1-3] as can clearly be seen in figs. 3b and 4.

Here we show the entropy-values as derived from the calculated fragment yields via the simple formula [1] against the thermodynamically obtained actual chemical equilibrium entropy values. If we would include only protons, neutrons and deuterons (fig.4a), the old d/p-formula[1] is a good approaximation, if only a few deuterons were produced. However, this assumption is invalidated by the recent high multiplicity data [ref.10, see also refs. 7,8 and 9]. The inclusion of fragments up to the α-particle changes the picture completely (figure 4b); the d/p formula is totally wrong at small entropies, it even exhibits a minimum at S/A~2.5. Also the improvements [2,3] neglect the decay of particle instable states and therefore overestimate drastically the true entropy at low entropies. They coincide with the correct result only for S/A>5. Also, we must point out that the entropy values extracted from this formula cannot fall below S/A ≈ 3.5. This is the origin of the confusing contradictory results obtained in ref. 10, when the analysis of ref. 3 is used.

Recently, experimental efforts have been made [7,8] to determine the break-up temperature directly from ratios of excited states to ground states in Lithium and Beryllium nuclei at bombarding energies around 50 MeV/nucleon. A surprising difference was found: γ-instable systems like $^7Be^*$(478 keV)/^{7}Be(gs) give T~500 keV, particle instable systems like ^{5}Li(16.66 MeV)/^{5}Li(gs) yield T~5 MeV, if the simple Boltzmann-Ansatz proportional to $e^{-E_i/T}$ is used for the yield ratio. Figure 5 shows that the reason for this paradoxical results is again the feeding of these channels by the sequential decay[4,7]: in the case of ^{7}Be, feeding (mainly to the ground state) from particle-instable fragments with bigger masses sets in at T~2 MeV. Then a ratio of 0.2 is obtained, independent of the actual temperature. Hence these ratios are not useful for a temperature measurement. On the other hand, ratios of particle-instable states, especially in the weakly bound ^{5}Li- and ^{6}Li-nuclei, show only a moderate distortion from the sequential decay. Therefore the Boltzmann-Ansatz can be used here as an approximation. A temperature of 5 MeV was derived from the 5 measured ratios in Ar+Au collisions at 60 MeV/nucleon[8].

Figure 6 displays the yields of 18 light, stable fragments, measured by B. Jacak et al.[9]. The experimental results are impact-parameter averaged, for this reason we fit only the heavy fragments with mass number >5, which supposedly origin predominantly from head-on collisions, while light fragments can occur also in grazing collisions (spectator fragments have not been counted in the experiments!). The wealth of heavy fragment yields is well fitted with one free parameter, the entropy S/A, thus

lending support to the assumption of chemical equilibrium.

We have also analyzed the recent high multiplicity selected data of the Plastic Ball group [10] with the present approach.

Fig. 7 shows the multiplicity dependence of the yields of d, t, ^{3}He, ^{4}He, ^{5}Li, ^{6}Li, ^{8}Li(curves in descending order) as normalized to the proton yields. Observe that the total number of clusters at the high multiplicity matches the number of free (unbound) protons. The number of bound protons therefore even exceeds the number of free protons. It would be interesting to study this dependence for the system Gold+Gold at somewhat lower energies and with even heavier clusters included, since there real multifragmentation events with a cluster number which exceeds by far the free proton number are to be expected. The multiplicity dependence of the yields in our calculation is deduced from an increase of the effective volume per nucleon in peripheral collisions which inceases the entropy per participant in non-central collisions above the thermodynamic infinite multiplicity value. This effect has been observed in cascade calculations[12].

The final figure 8 summarizes the results of our entropy - fits to various experiments. The four low energy Ar+Au points display the fits to the experiments mentioned above [8,9], while the high energy (with the help of figure 3b) Nb+Nb and Ca+Ca points are extracted from the asymptotic d_{like}/p_{like} ratios measured with the plastic ball at the Bevalac[10]. Note that the entropies obtained are very low, increasing from ~1.5 to ~ 2.5 units per nucleon for bombarding energies ranging from 40 to 1000 MeV/nucleon. This may be indicative for an extremely large nuclear incompressibility, which would be in accord with results from other heavy ion data[11].

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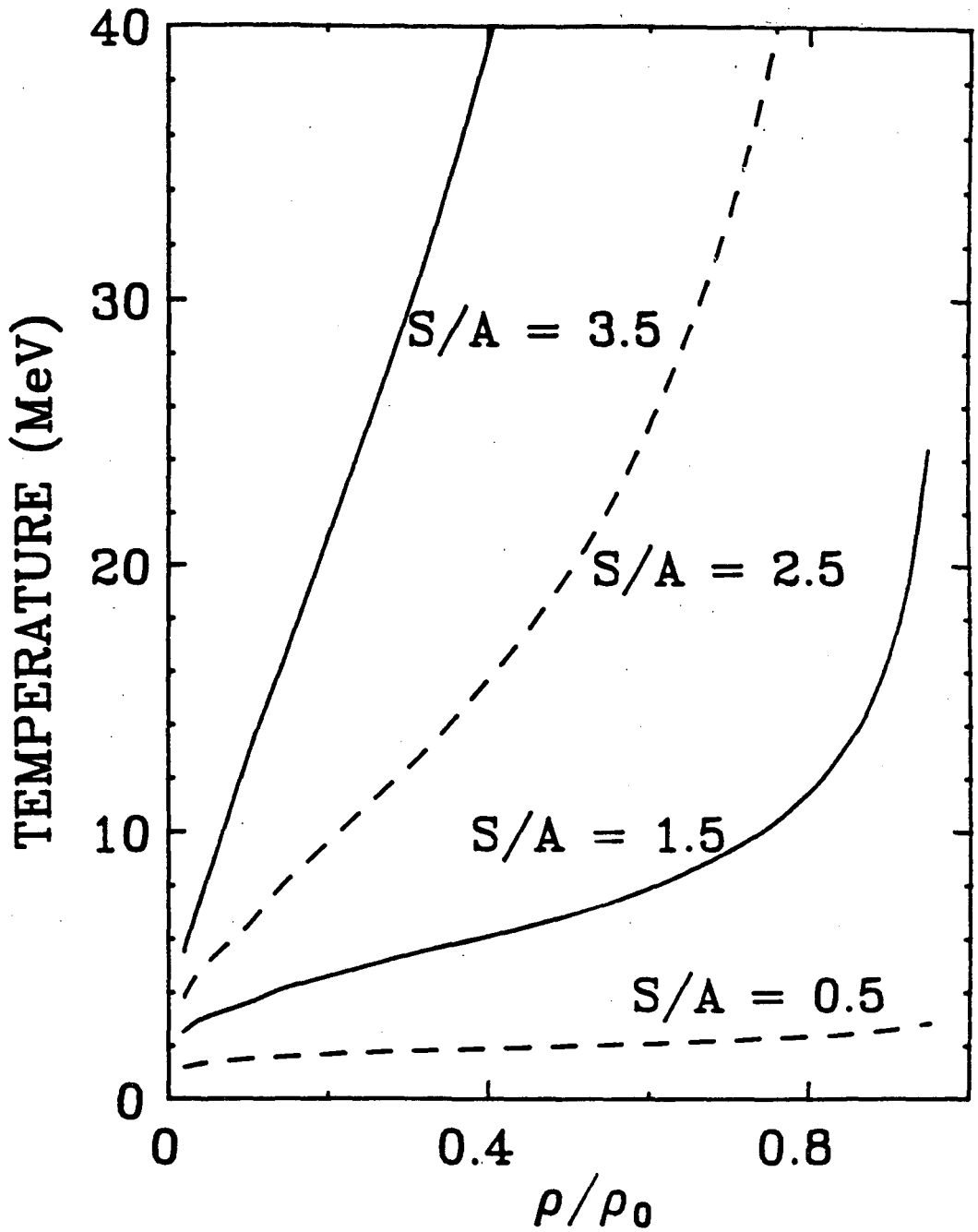

Fig.1: Primordial path of our system for 4 different entropies in the case of N=Z.

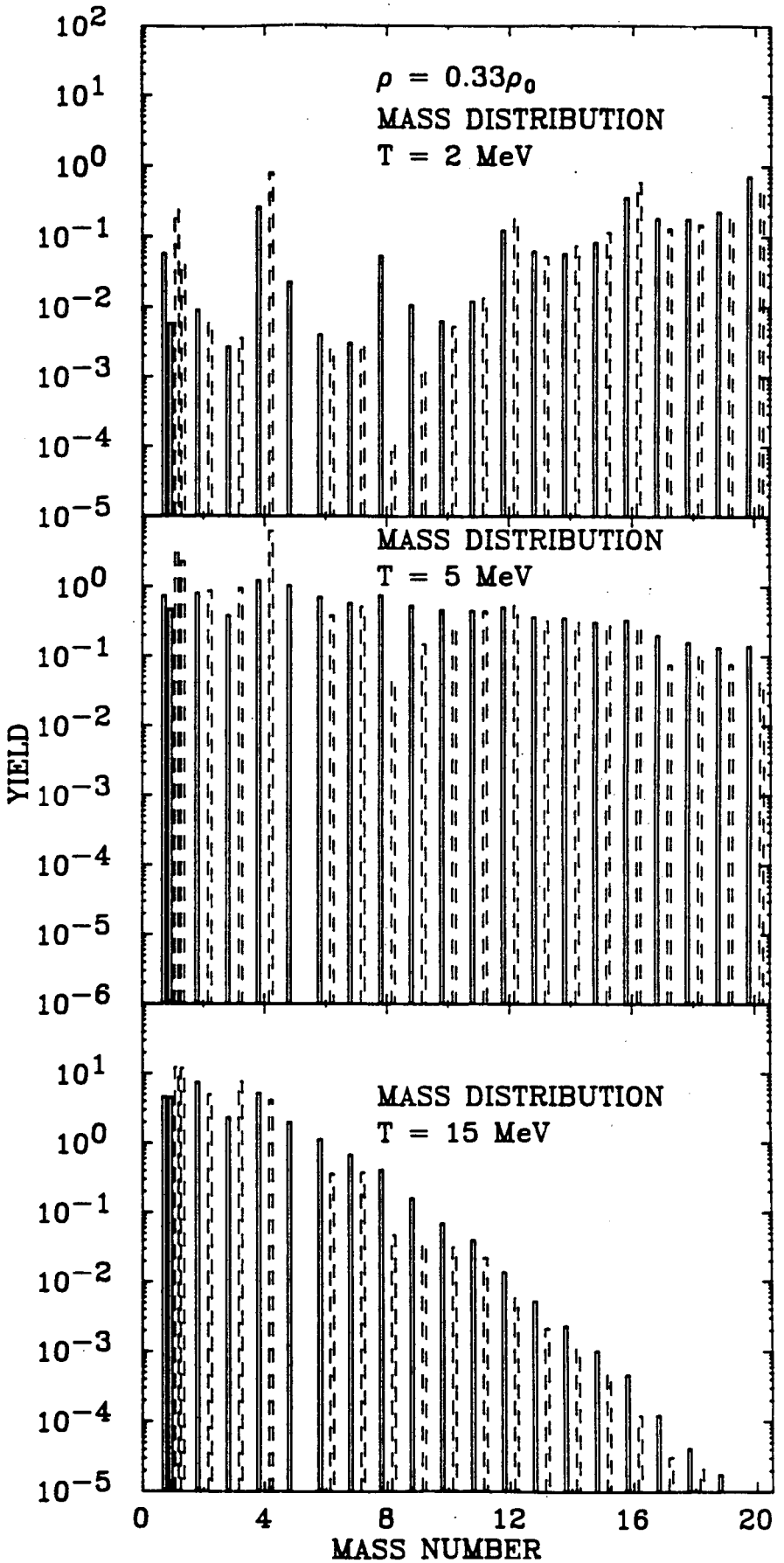

Fig.2: Mass distributions for N=Z. Solid lines display primordial yields, dashed lines yields after subsequential decay.

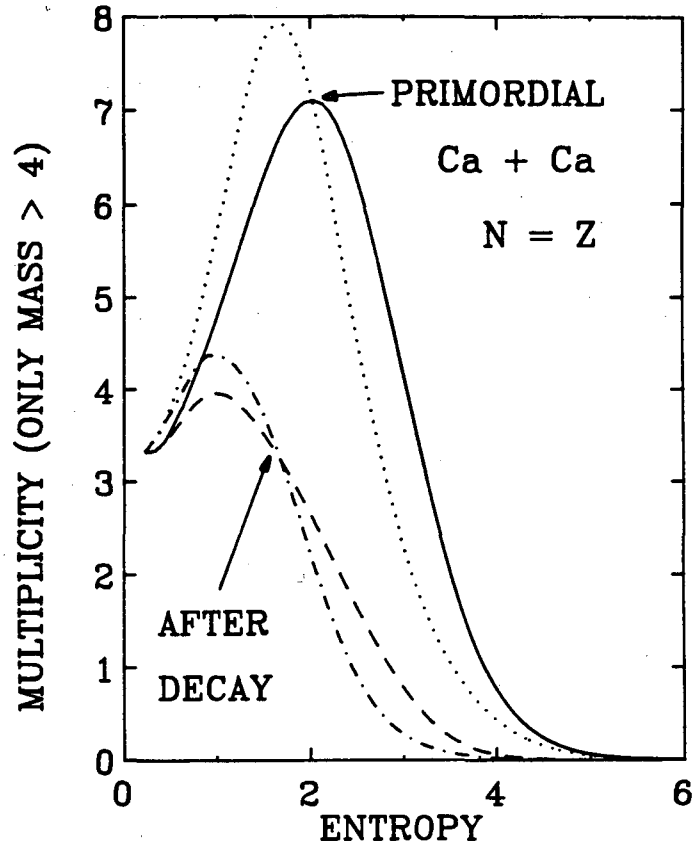

Fig.3a: The entropy-dependence of the multiplicity of heavy fragments for two different break-up densities, ρ-0.1 ρ_0, solid and dashed line; ρ=0. 5ρ_0 dotted and dotted dashed line.

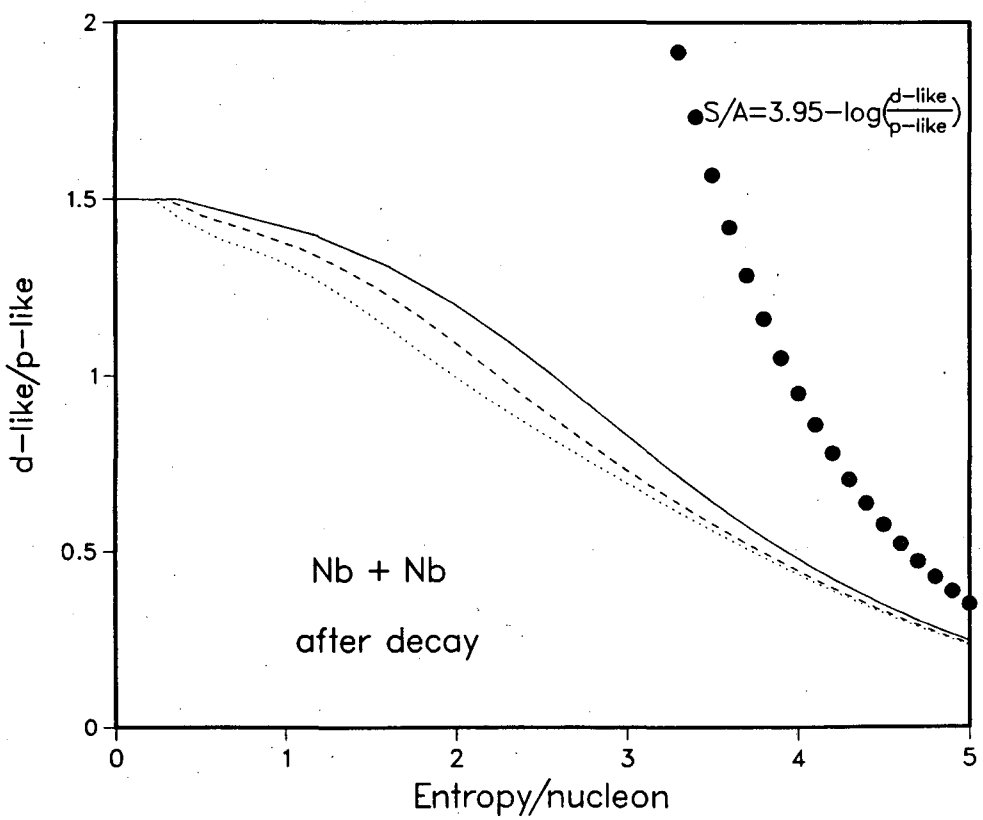

Fig.3b: The d_{like}/p_{like} dependence on the entropy for the break-up densities ρ=0.1, 0.33 and 0.8 ρ_0.

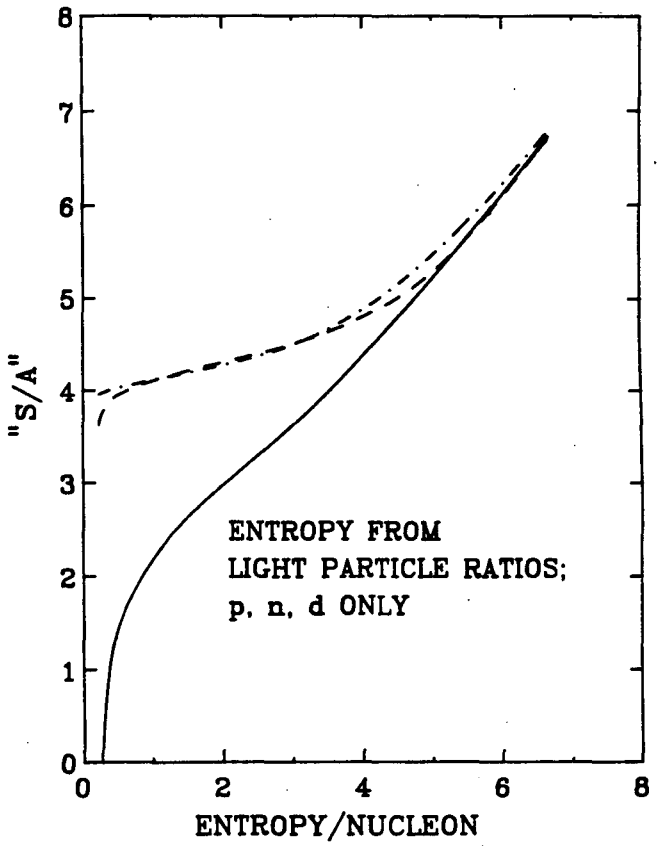

Fig.4a: The entropy values derived from the calculated d and p yields via the formulae of Siemens, Kapusta (solid line), Bertsch, Cugnon[2] (dotted-dashed line), and Kapusta[3] (dashed line) against the thermodynamic entropy for Ca+Ca at $\rho=0.1\ \rho_0$. Only d and p,n have been included into the chemical equilibrium calculation.

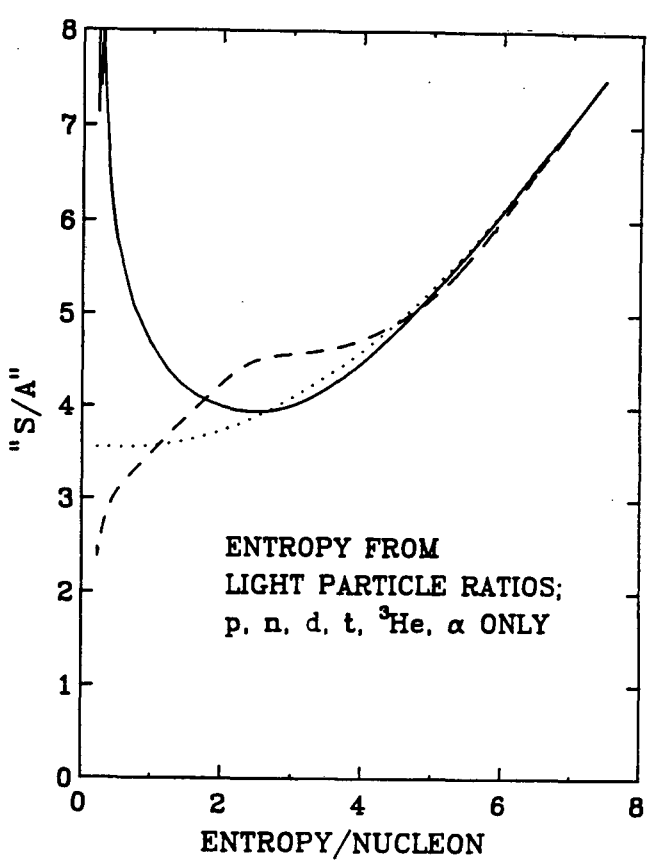

Fig.4b: Same as 4a, but t, ^{3}He and α-particles are also included.

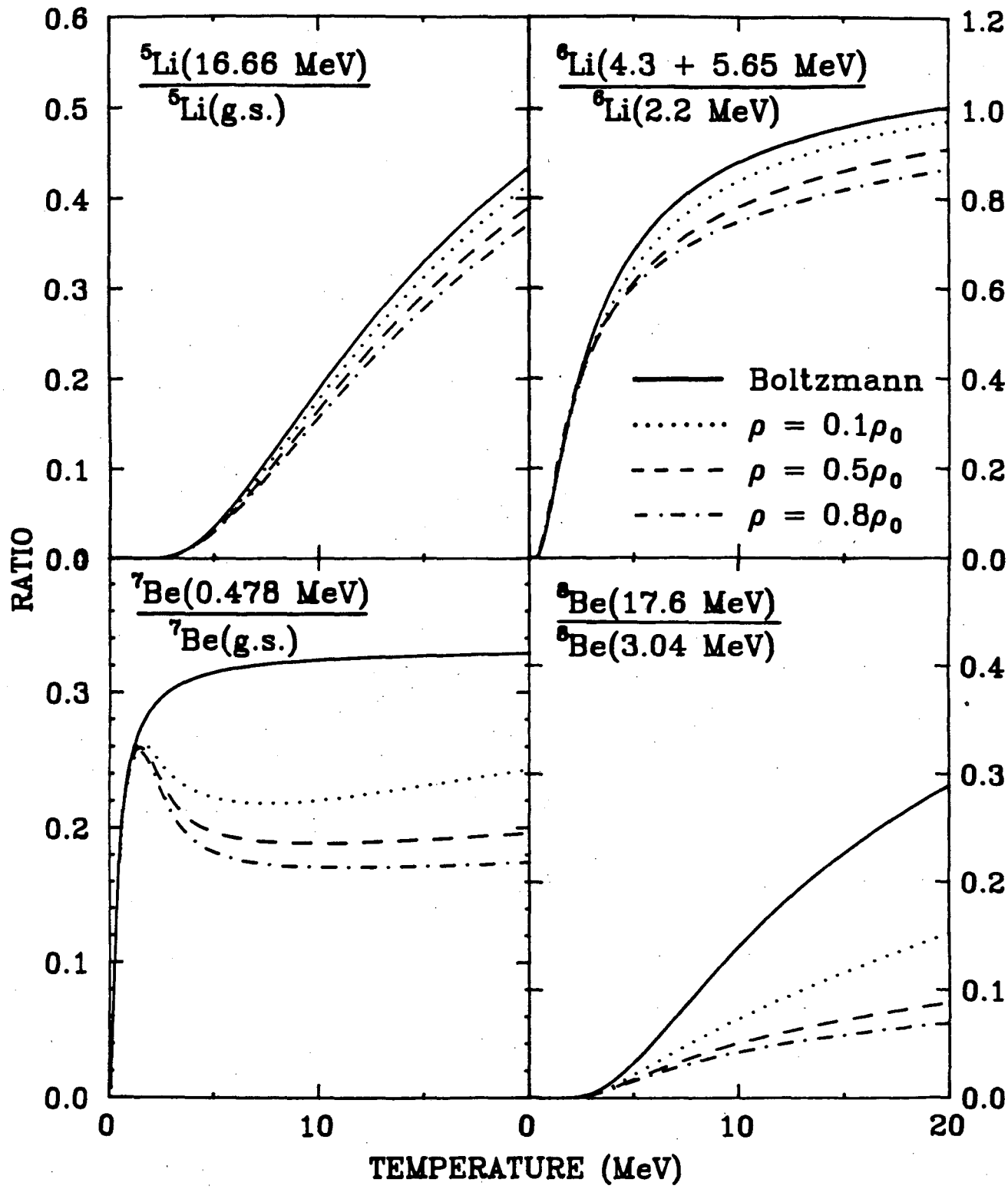

Fig.5: Ratios of excited states to ground states for Ar+Au against the temperature. Solid lines show the ratio in the case of a pure Boltzmann distribution.

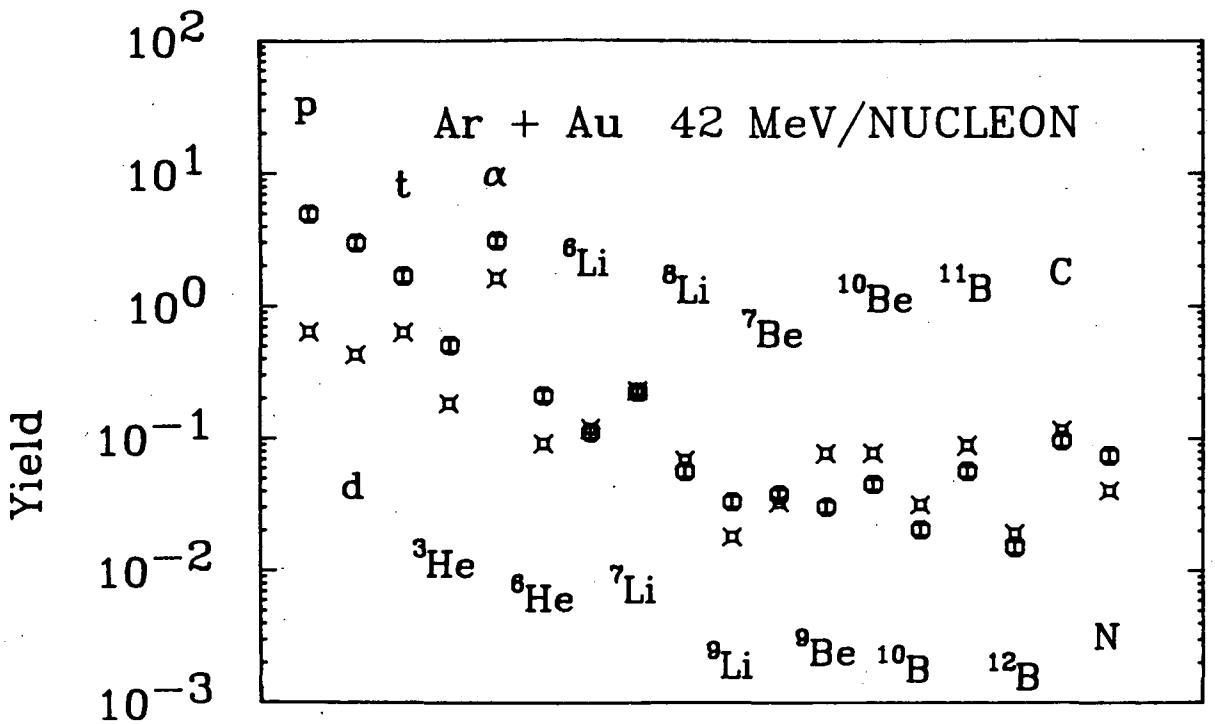

Fig.6: Yields of 18 stable fragments[9]. Circles are the experimental results (rapidity-selected for participants), diamonds show the result of our fit at $\rho=0.5\ \rho_0$.

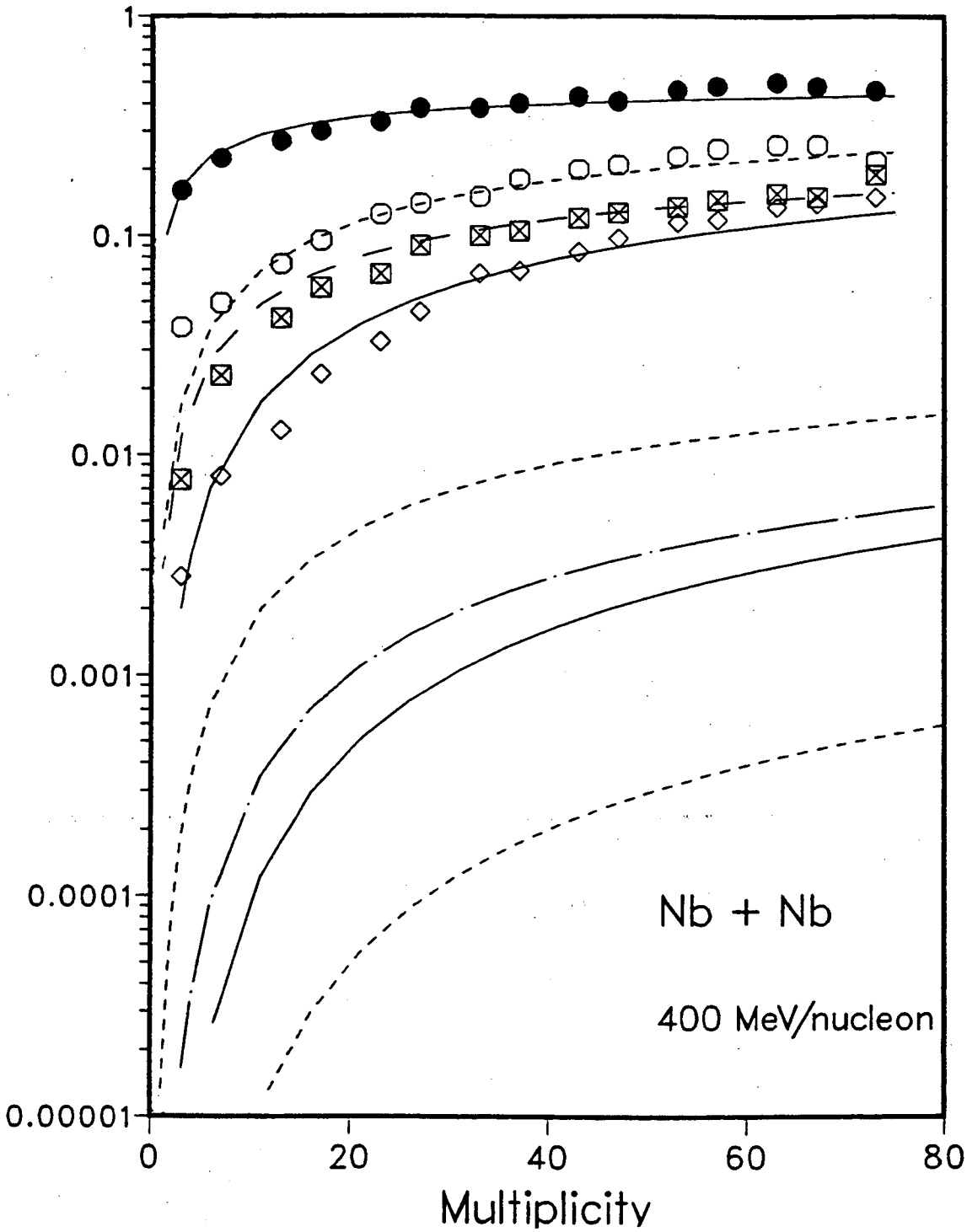

Fig.7: The multiplicity dependence of d, t, ^{3}He, ^{4}He, ^{5,6,7,8}Li-to-proton ratios as measured by the Plastic Ball collaboration[10] for Nb (400 MeV/nucleon) + Nb. The curves are the results of the quantum statistical model calculation, which lead to an asymptotic entropy value S/A ($M\to\infty$)≈2.5.

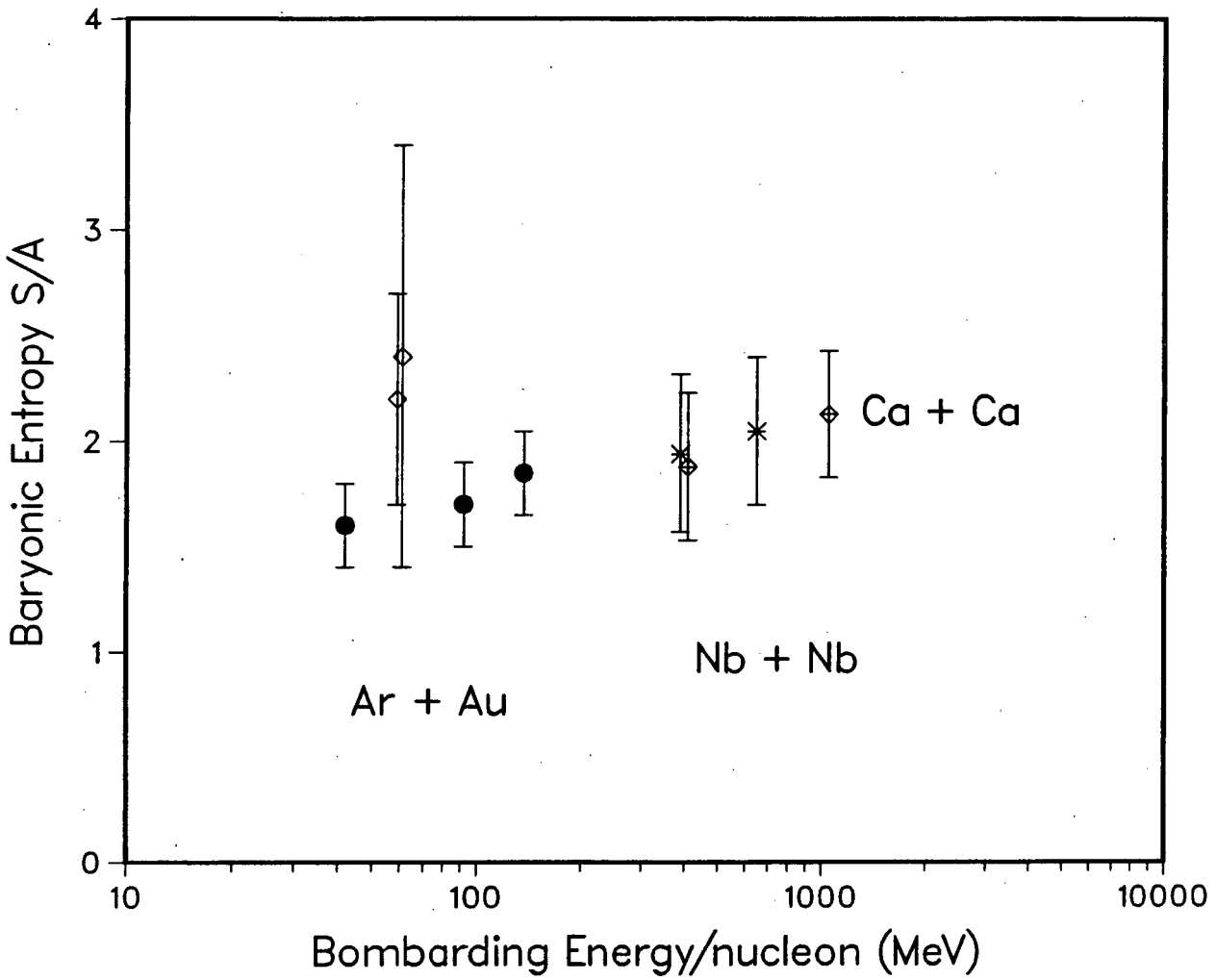

Fig.8: Resulting entropy values S/A from our fits to different experiments[8-10]. Error bars are due to the uncertainty in the break-up density, we assume $0.1\rho_0<\rho<0.8\rho_0$.

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