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Entropy from Fragment Yields in Nucleus-Nucleus Collisions around 100 MeV/nucleon

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Abstract

Recent experimental data for light particle and complex fragment emission are compared to the results of a microcanonical statistical fragmentation model. The entropy produced in the reactions is extracted by varying the breakup temperature and density. The best fit to the data is nearly independent of the temperature and density. The extracted entropy is somewhat higher for light particles than for complex fragments.

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1. Introduction

Multifragmentation processes play an important role in sufficiently violent nuclear collisions.[1] The many fragments in the final state of these collisions are frequently described in terms of statistical concepts.[2] In particular, the entropy per nucleon in the final state appears to be a very useful quantity. The physical reason for the usefulness of the entropy is related to the fact that the entropy/nucleon does not change significantly in the expansion stage of the collision.[3] Entropy, therefore, transmits information to the observer about the hot and dense stage of the collision.[4] On a more technical level, entropy is useful because it can be extracted from fragment yields with good accuracy, in contrast to quantities like the breakup temperature or density.[5]

The approximate uniqueness of the entropy in the final state of central Ca + Ca and Nb + Nb collisions was demonstrated recently at beam energies in the 0.4 - 1 GeV/nucleon range.[6] Collisions at lower beam energies are also extensively studied experimentally.[7] At these energies information on higher-mass fragments than detected with the Plastic Ball/Wall[8] is available[9] in addition to the yields of fragments with $A \leq 4$. The significant theoretical interest in the lower energy collisions[10] is partly due to the expected liquid-vapor phase transition in nuclear matter.[11] Since the critical temperature associated with this phase transition is predicted by most models to be below $T_c = 20$ MeV,[12] it is necessary to study multifragmentation at beam energies on the order of 100 MeV/nucleon to learn about phenomena related to the liquid-vapor phase coexistence in nuclear matter. We will therefore consider the available data on Ar + Ca collisions at beam energies 137 MeV/nucleon, 92 MeV/nucleon and 42 MeV/nucleon[9] and use the method proposed in Ref. 6 to extract the entropy/nucleon achieved in the final states of these reactions. Note that in the experiments reported in Ref. 9 intermediate rapidity fragments were selected to ensure that the disassembly of the hot participant source is studied. This technique should be contrasted to the filtering of the data used earlier,[6] where only the highest multiplicity bins were considered in order to select the most central events. As a consequence, the typical disassembling system is much smaller in the present sample and the effects of microcanonical statistics are expected to be more important. Since the energy is relatively low, quantum statistics effects should also be more noticeable.[13] However, it is not expected that the use of Boltzmann statistics seriously compromises our results for the systems investigated here.

The rest of the paper is organized as follows. In Section 2 we briefly present our method of extracting the entropy from fragment yields. Section 3 contains our results for the Ar + Ca system at three different beam energies. Finally we draw a few conclusions from the analysis in Section 4.

2. Entropy extraction

Due to the possibility of systematic errors in the absolute normalization of measured cross sections, we focus on the relative fragment abundances as experimental information. Theoretical models should simultaneously reproduce the measured relative fragment yields. The results of any calculation can be compared to these data utilizing a least-square procedure in terms of the theoretical (th) and experimental (exp) fragment yield ratios. Consider

$$\Sigma = \sum_i w_i[(Y_i/Y_p)_{th} - (Y_i/Y_p)_{exp}]^2 \tag{1}$$

where Y_i is the yield of fragments of type i, Y_p is the proton yield and w_i is a weight factor. In our method we weight the different fragment species according to their nucleon content[6] to take into account the amount of nuclear matter contributing. We take

$$w_i = A_i^2/4 \tag{2}$$

where A_i is the mass number of fragment i. In this way the coefficient of the squared difference of the theoretical and experimental deuteron/proton ratios is unity in (1). The summation can be extended to all measured fragments or one can take a subset of the detected fragment types. This flexibility is particularly convenient when the entropy carried by light fragments is compared to that carried by heavier fragments.

The theoretical yields in eq. (1) were calculated with the FREESCO event generator[14] in the mode corresponding to treating the participant source only. We assume that a participant source of temperature T and density n was created in the collision and generate a sample of 200 events for each pair of variables following a method[15] identical to the one used in the analysis of central Ca + Ca and Nb + Nb collisions at higher energies earlier.

A method contrasting with the present one is to extract the entropy from the data starting from the simple formula connecting the entropy per nucleon of a classical, charge symmetric gas of nucleons and deuterons to the deuteron-to-proton ratio[16] R_{dp} via

$$S = 3.945 - \ell n\, R_{dp} \tag{3}$$

This relation has been substantially generalized,[17] as detailed e.g. in Ref. 6. Limitations of this approach are extensively discussed in Ref. 13.

We have studied the Ar + Au collision at 42 MeV/nucleon beam energy in an earlier work.[18] The nuclear liquid-vapor phase coexistence may be encountered in this energy region.[4] It is interesting to recall in the present context that it was not possible to describe the observed fragment yields with one single source. Two sources with different densities and the same temperature (or with different temperatures and the same density), however, gave a reasonable fit to the data. One can think about the two sources with different densities as the liquid and vapor phases of nuclear matter in equilibrium at the given temperature. If the selection of midrapidity fragments is satisfactory to identify the hot participant source, then the liquid-vapor phase coexistence is probably the more acceptable choice than two geometrically separate regions with different temperatures. In the present work we will further study the possibility of the appearance of two phases in nuclear collisions at beam energies ~100 MeV/nucleon by exploring the possibility of associating separate entropy values to the light (proton - alpha) and detected heavier fragments of the collision.

3. Results

In Fig. 1 we show the value of Σ for Ar + Ca at E_{beam}= 137 MeV/nucleon as a function of the temperature (T) and the entropy/nucleon (S/A) with the summation restricted to light fragments ($A \leqq 4$) in eq. (1). Different symbols correspond to different temperatures in the range 10 MeV $\leqq$ T $\leqq$ 60 MeV, as indicated in Fig. 1. Each point represents an ensemble average of 200 events generated microcanonically with the FREESCO event generator. The calculated results obtained with different temperatures are seen to fall on a nearly universal curve. The T = 10 MeV points start to deviate from this curve in agreement with the findings of Ref. 6. We extract the minimum at S/A = 3.9±0.2 with a value of Σ = 0.015 from Fig. 1. The small value of Σ indicates that these fragment yields are described simultaneously with good accuracy. Notice that for T = 10 MeV the minimum of Σ occurs at a slightly higher entropy S/A = 4.35 with a smaller value of Σ (Σ = 0.005).

Figures 2 and 3 display similar results at E_{beam}= 92 MeV/nucleon and 42 MeV/nucleon, respectively. We extract an entropy value S/A = 3.9±0.3 at 92 MeV/nucleon, identical to that of the 137 MeV/nucleon case within the accuracy of the method. With decreasing beam energy we arrive at a stage where the results can not be interpreted in terms of a nearly universal curve anymore (Fig. 3). If one assumes that the procedure still has some validity at this low energy, the following two statements can be made: (i) the minimum of the T = 10 MeV curve is much deeper than that of the higher temperature isotherms in Fig. 3, and therefore the temperature is close to 10 MeV in the E_{beam} = 42 MeV/nucleon case, (ii) the width of this minimum is narrower than at 137 and 92 MeV/nucleon leading to a sharper entropy determination, S/A = 3.2±0.1.

Our results for the entropy carried by the heavier fragments (Li-N) are presented in Figs. 4-6 scaled by a factor of 30. The heavier fragment abundances would contribute modestly to a Σ restricted by detection capabilities only and the overall entropy of the final state is thus determined by the light fragments. The minima are less pronounced in Figs. 4-6 than in Figs. 1-3. We extract $S/A = 3.3^{+0.4}_{-0.3}$, $3.1^{+0.5}_{-0.3}$ and 3.0±0.1 for E_{beam} = 137 MeV/nucleon, 92 MeV/nucleon and 42 MeV/nucleon, respectively. Although the applied statistical model does not exhibit a phase transition, based on the fact that the temperatures extracted from the energy spectra of different fragments appear to be independent of fragment mass,[7] it is tempting to assume that the relatively lower entropies exhibited by the heavier fragments ($\Delta(S/A)$ = 0.6, 0.8 and 0.2, respectively) reflect the breakup of a higher density (liquid) source in thermal equilibrium with a lower density (vapor) source.

It is important to remember that our results at 42 MeV/nucleon (Figs. 3 and 6) can not be considered to fit on universal curves on the $(S/A, \Sigma)$ plane. This fact indicates that the model needs improvement at the lower energies to remove ambiguities in the extracted entropy for different assumed temperatures. In particular, Coulomb and attractive interactions of the fragments need to be incorporated. Attractive interactions should bring about an explicit phase transition in the model, which is not contained in the present equation of state.[19] On the other hand, effects of microcanonical statistics (correctly taken into account in the model) also become more important at low beam energies, where the available excitation energy is strongly limited.

4. Conclusion

The above analysis indicates the presence of two separate sources of midrapidity fragments in Ar + Ca collisions at least at beam energies $E_{beam} = 137$ MeV/nucleon and 92 MeV/nucleon. The entropies extracted from the light fragments ($A \leqq 4$) are in qualitative agreement with the values presented for the Ar + Au system in Ref. 9. However, according to this analysis the entropies are dominated by the contribution of the light fragments, while the inclusion of heavier fragments results in substantially lower values of the entropy (at least in the Ar + Au system) in calculations carried out with the quantum statistical model.[9,13] It was noticed earlier,[9] that target spectator fragments carry a lower entropy than participants; in the present work we attempt to make a distinction between two separate sources of midrapidity fragments. One possibility for two such sources is offered by the assumption of two, geometrically separate regions within the participant matter. To test this hypothesis similar experiments with strict impact parameter selection would be helpful. Another and particularly appealing possibility is the assumption that the system consists of liquid and vapor phases in thermal equilibrium at breakup; the heavier fragments with lower entropy correspond to the fragmentation of the liquid phase, while the entropy extracted from the light fragments reflects the properties of the vapor. The fits are not sufficiently good at 42 MeV/nucleon beam energy. The model needs to be improved further to satisfactorily describe collisions with beam energies below ~100 MeV/nucleon.

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Figure Captions

Fig. 1

The quantity Σ (see eq.(1)) as a function of the entropy per nucleon for the reaction Ar + Ca at 137 MeV/nucleon, for temperatures ranging from 10 to 60 MeV. The different points at the same temperature correspond to different breakup densities. The comparison is restricted to light particles: p-α.

Fig. 2

Same as Fig. 1 for the reaction Ar + Ca at 92 MeV/nucleon.

Fig. 3

Same as Fig. 1 for the reaction Ar + Ca at 42 MeV/nucleon.

Fig. 4

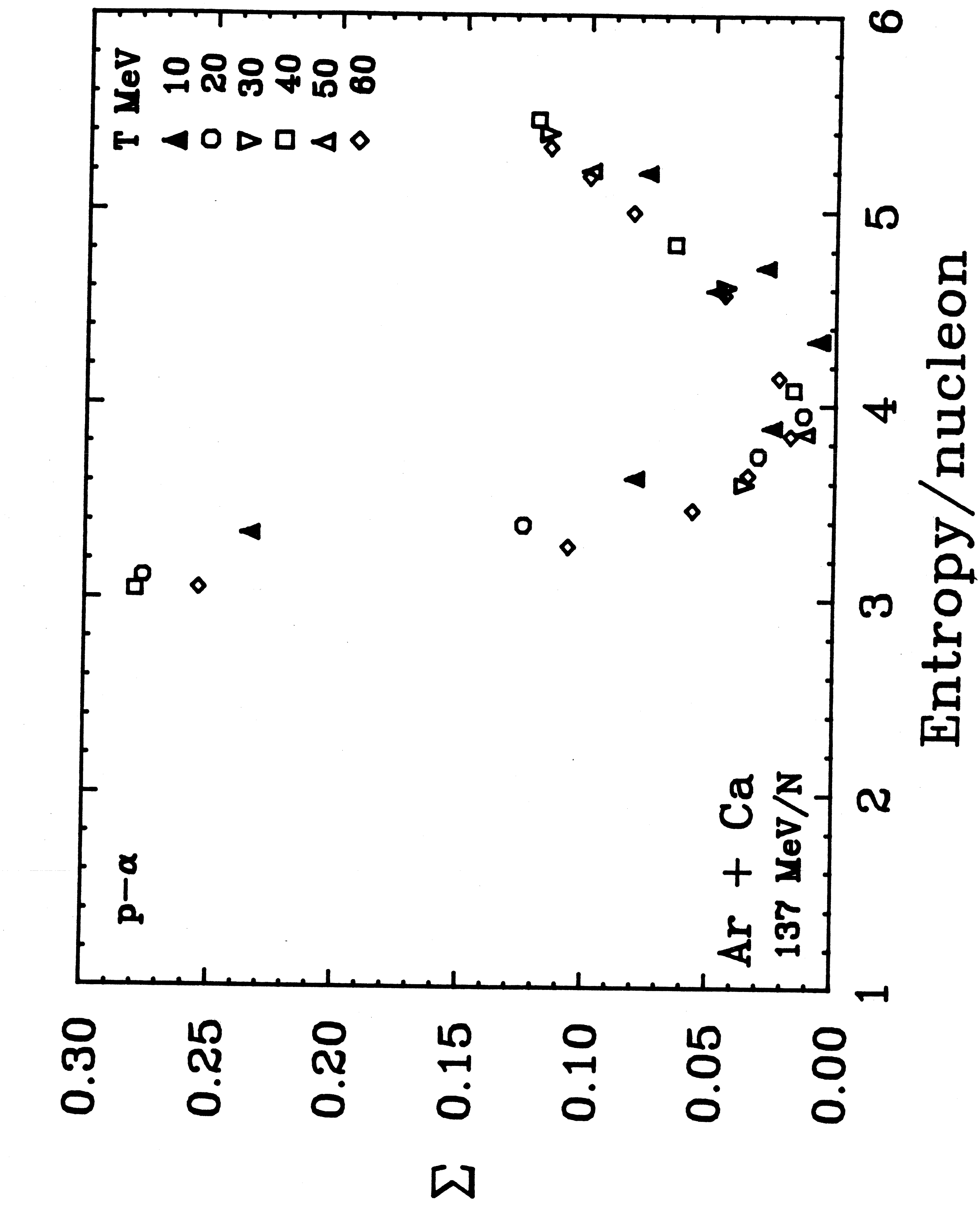
The quantity Σ (see eq.(1)) as a function of the entropy per nucleon for the reaction Ar + Ca at 137 MeV/nucleon, for temperatures ranging from 10 to 60 MeV. The different points at the same temperature correspond to different breakup densities. The comparison is restricted to complex fragments: Li - N. The Σ values are multiplied by 30.

Fig. 5

Same as Fig. 4 for the reaction Ar + Ca at 92 MeV/nucleon.

Fig. 6

Same as Fig. 4 for the reaction Ar + Ca at 42 MeV/nucleon.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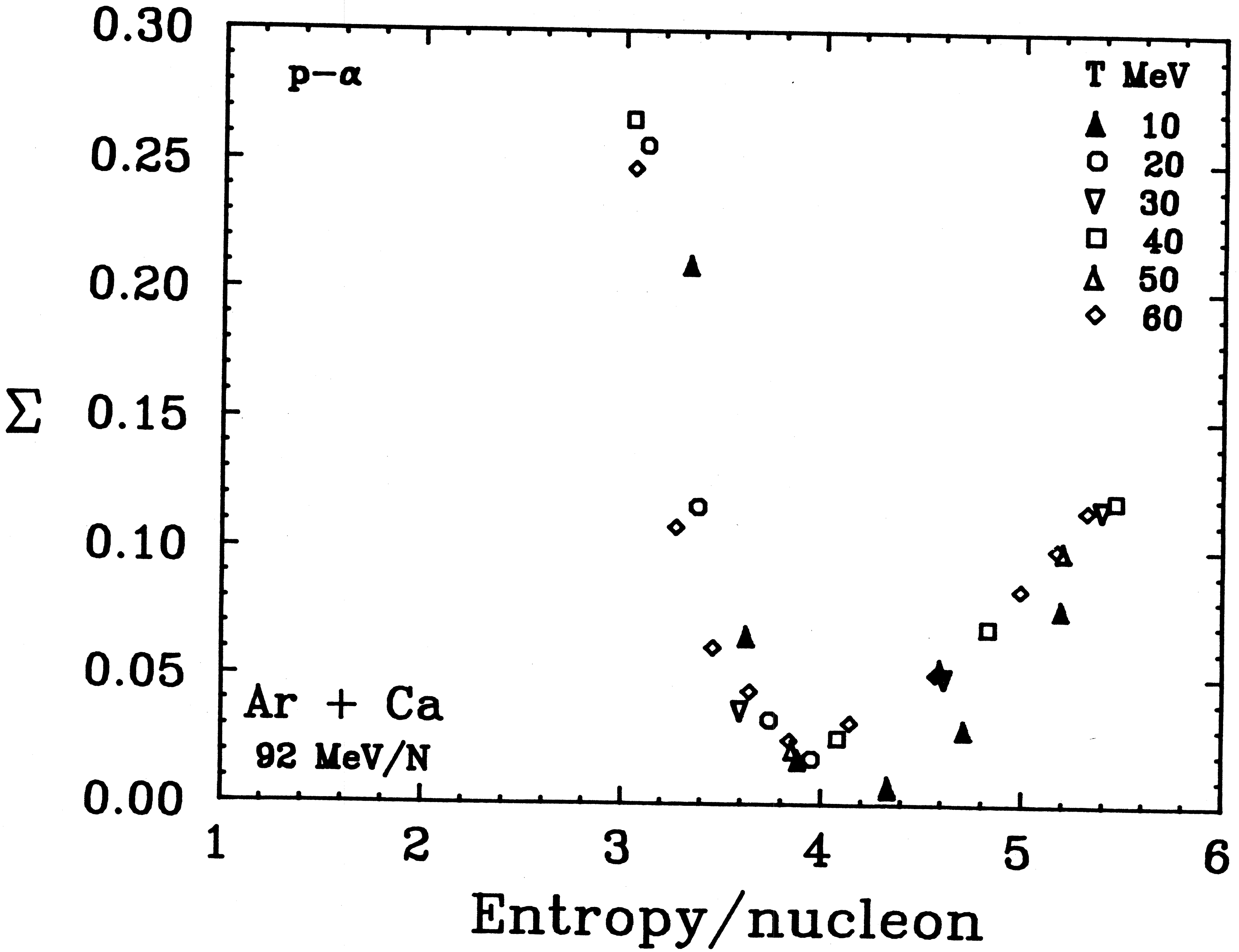
0.25
0.20
0.15
0.10
0.05
0.00
1
2
3
4
5
6
Entropy/nucleon
p–α
Ar + Ca
137 MeV/N
T MeV
▲ 10
○ 20
▽ 30
□ 40
△ 50
◇ 60

Fig. 1


p–α
T MeV
▲ 10
○ 20
▽ 30
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△ 50
◇ 60
Ar + Ca
92 MeV/N
Σ
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1
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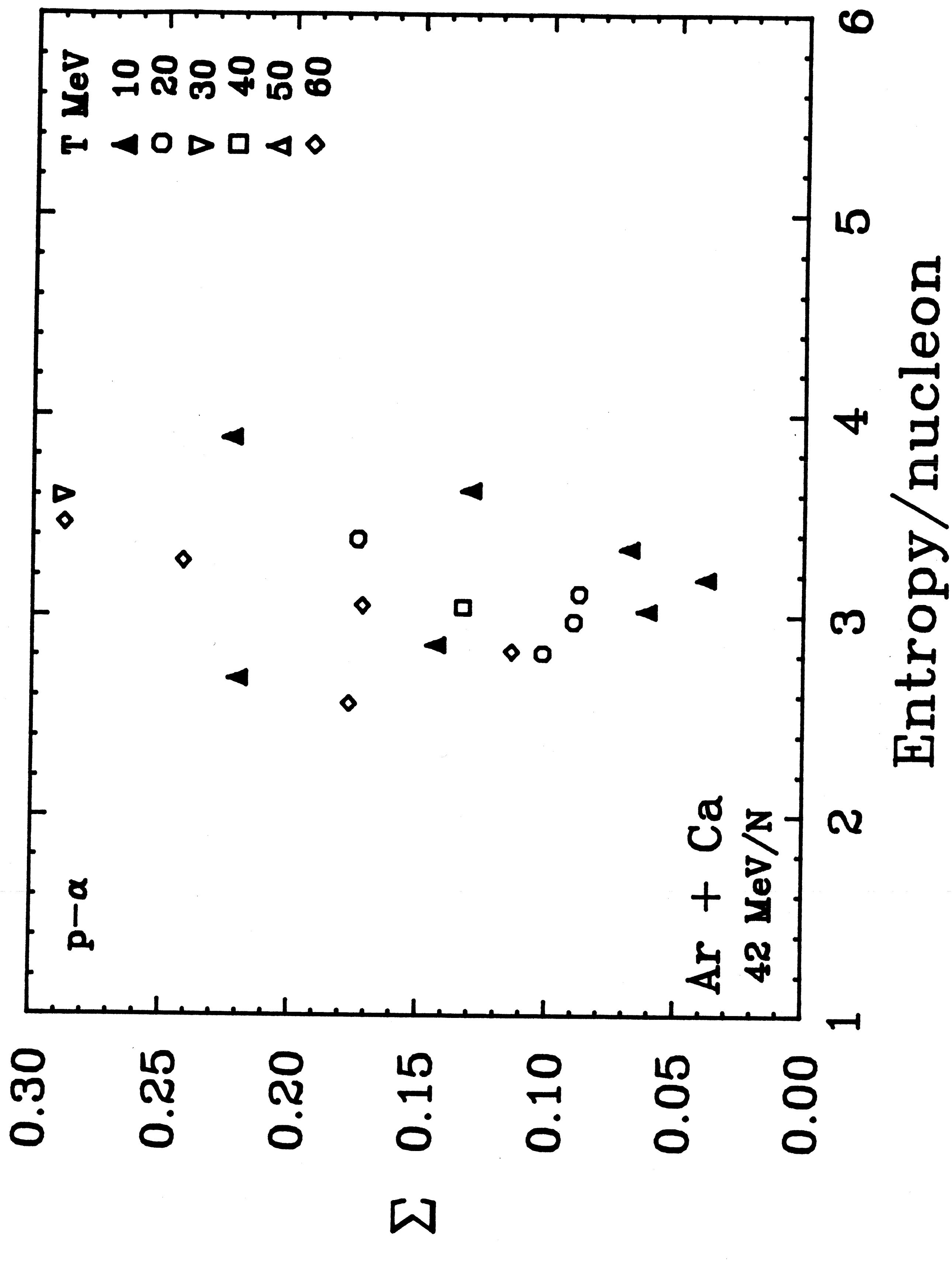
Entropy/nucleon

Fig. 2


p–α
Ar + Ca
42 MeV/N
T MeV
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Σ
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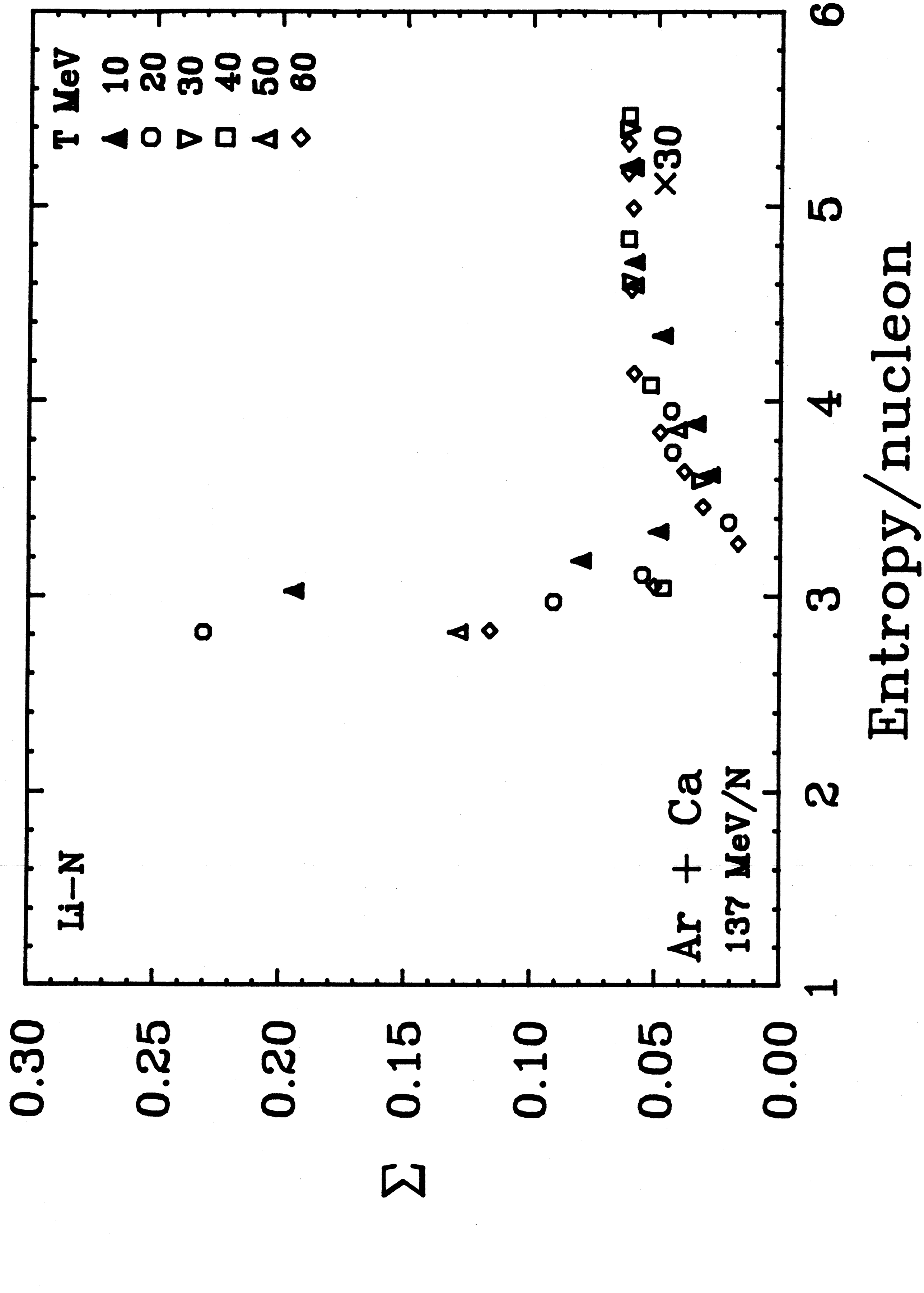
6
Entropy/nucleon

Fig. 3


Σ
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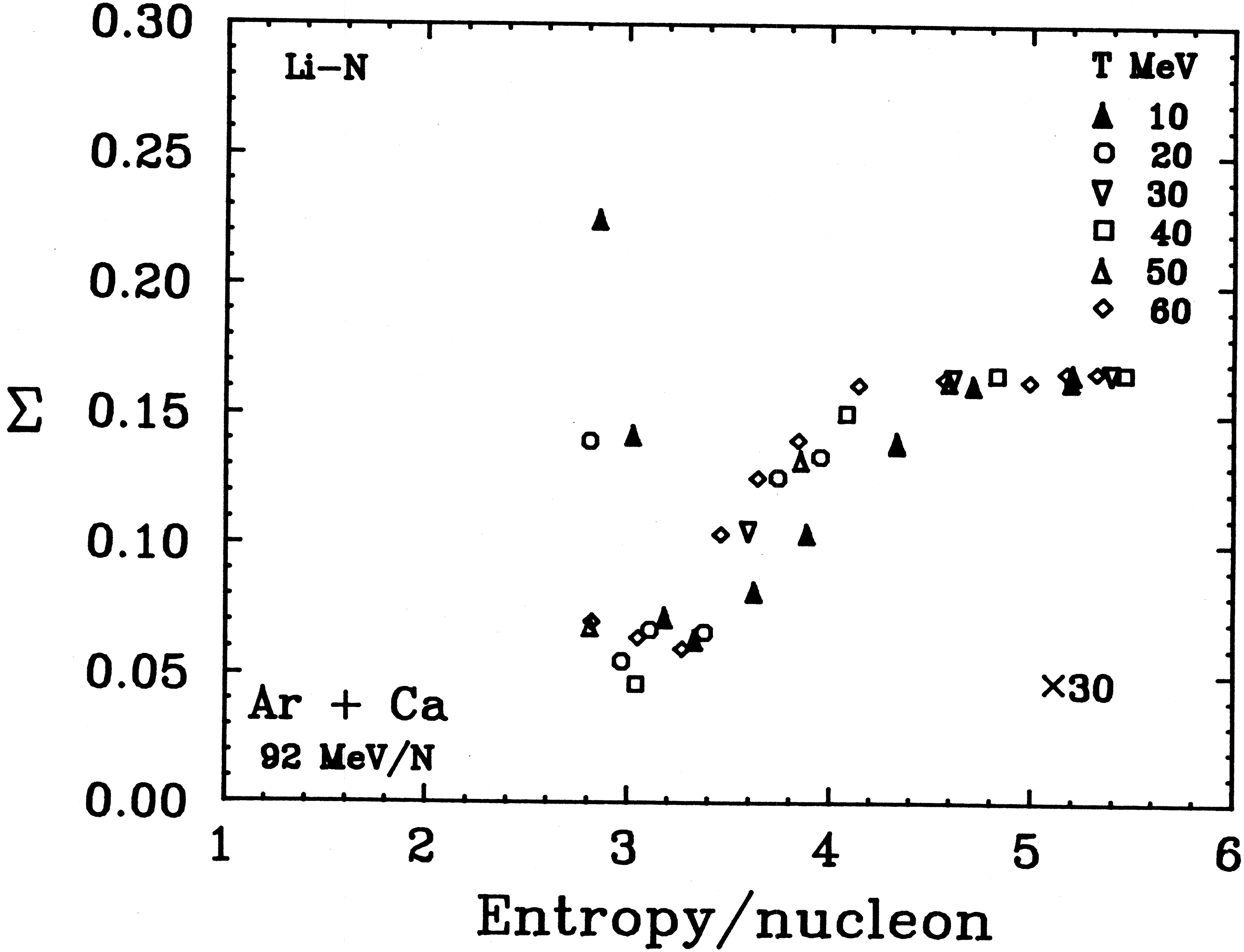
Entropy/nucleon
Li-N
Ar + Ca
137 MeV/N
T MeV
▲ 10
○ 20
▽ 30
□ 40
△ 50
◇ 60
×30

Fig. 4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Entropy/nucleon
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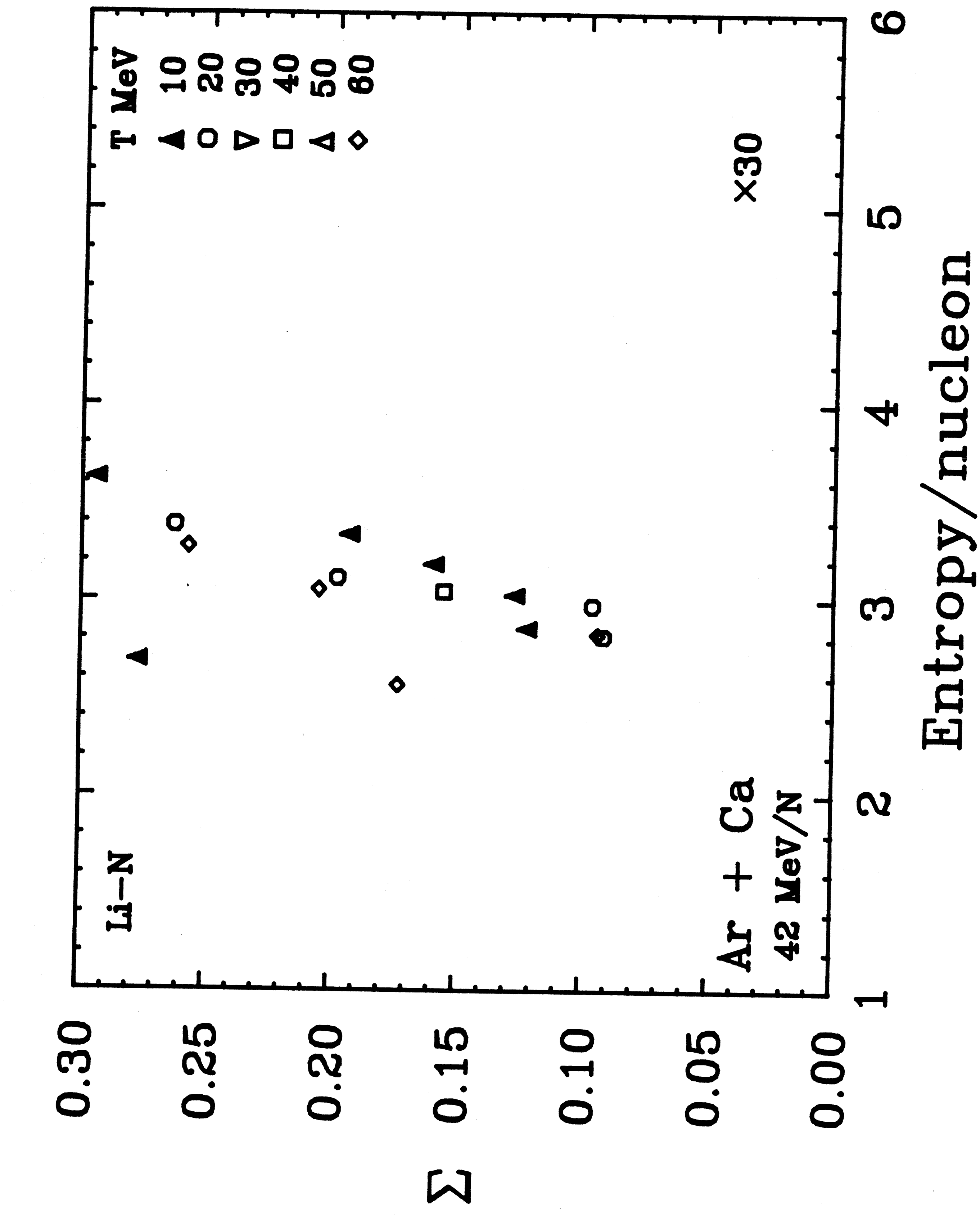
×30
Ar + Ca
92 MeV/N

Fig. 5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Entropy/nucleon
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Li-N
Ar + Ca
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Fig. 6