Strangeness and Pion Production as Signals of QCD Phase Transition

Marek Gaździcki §

Institut für Kernphysik, Universität Frankfurt
August–Euler Str. 6, D–60486 Frankfurt, Germany

Abstract. A systematic analysis of data on strangeness and pion production in nucleon–nucleon and central nucleus–nucleus collisions is presented. It is shown that at all collision energies the pion/baryon and strangeness/pion ratios indicate saturation with the size of the colliding nuclei. The energy dependence of the saturation level suggests that the transition to the Quark Gluon Plasma occurs between 15 A·GeV/c (BNL AGS) and 160 A·GeV/c (CERN SPS) collision energies. The experimental results interpreted in the framework of a statistical approach show that the effective number of degrees of freedom increases in the course of the phase transition and that the plasma created at CERN SPS energies may have a temperature of about 280 MeV (energy density $\approx$ 10 GeV/fm^{-3}). The presence of the phase transition can lead to the non–monotonic collision energy dependence of the strangeness/pion ratio. After an initial increase the ratio should drop to the characteristic value for the QGP. Above the transition region the ratio is expected to be collision energy independent. Experimental studies of central Pb+Pb collisions in the energy range 20–160 A·GeV/c are urgently needed in order to localize the threshold energy, and study the properties of the QCD phase transition.

Talk given at International Symposium on 'Strangeness in Quark Matter 1997', Thera (Santorini), Greece, April 14–18, 1997.

---

§ e–mail: marek@ikf.uni–frankfurt.de

1. Introduction

In this paper we review the recent status of our search for a QCD phase transition to the Quark Gluon Plasma [1] by a systematic analysis of strangeness and pion (entropy) production in nuclear collisions. There are important reasons to select strangeness [3] and entropy [2] as basic observables. Both are defined in any form of strongly interacting matter. Their equilibrium values are directly sensitive to the basic properties of matter: effective number of degrees of freedom and their effective masses. Entropy and strangeness production are believed to be produced at the early stage of the evolution of a system created in nuclear collisions and therefore they can allow us to 'measure' properties of matter at very high energy densities.

Our strategy of data† analysis [4, 5, 6, 7, 8, 9] reviewed here can be summarized as follows:

1. We study the dependence of the properly normalized entropy (mainly determined by pion multiplicity) and strangeness (mainly determined by kaon and hyperon yields) production on the volume of the colliding nuclear matter at a fixed collision energy. We demonstrate that a fast saturation occurs. The simplest qualitative interpretation is, that equilibration of entropy and strangeness takes place (Section 2).
2. We study the dependence of the saturation levels on the collision energy. We demonstrate that the saturation levels for both entropy and strangeness show an unusual change between AGS (≈15 A·GeV/c) and SPS (≈160 A·GeV/c) energies. We interpret this effect as due to the localization of the threshold energy for the QGP creation in the above energy range (Section 3).
3. Finally, we formulate a simple statistical model for entropy and strangeness production in nuclear collisions and show that the experimental results at SPS energes can be quantitatively described assuming creation of a QGP (Section 4). A critical discussion of the basic assumptions used in the model is given at the end of this section.

2. Volume Dependence

Experimental data on pion‡ and strangeness production in central nucleus–nucleus (A+A) and all inelastic nucleon–nucleon (N+N) collisions are shown in Fig. 1 as a function of the number of participant nucleons, $\langle N_P \rangle$, for various collision energies. In order to eliminate a trivial volume dependence, the normalized multiplicities are studied:

$$\frac{\langle \pi \rangle}{\langle N_P \rangle} \tag{1}$$

and

$$E_S \equiv \frac{\langle \Lambda \rangle + \langle K + \overline{K} \rangle}{\langle \pi \rangle}, \tag{2}$$

where $\langle \pi \rangle$, $\langle \Lambda \rangle$, and $\langle K + \overline{K} \rangle$ are the mean multiplicities of pions, $\Lambda(+\Sigma^0)$ hyperons, and kaons and antikaons, respectively. For all energies a similar behaviour is observed: a rapid change between results for N+N interactions and intermediate mass nuclei

---

† Data obtained by about 100 different experiments are used. The references to the original experimental works can be found in the compilation papers [4, 5, 6].

‡ Here we use pion multiplicity instead of entropy in order to start the analysis from 'raw' experimental data. An improved experimental estimate of entropy is given in the next section.

($\langle N_P \rangle \approx 50$) is followed by a well defined region in which the normalized pion and strangeness production is almost constant. We interpret the observed saturation as a result of an equilibration of entropy and strangeness yields. As the production rates are steeply decreasing functions of the temperature the equilibration can be expected to happen at the early stage of the collision. Thus the measured equilibrium values may reflect the properties of the initially created matter.

3. Energy Depenedence

The collision energy dependence of the normalized entropy and strangeness production is shown in Fig. 2. The energy dependence is studied using the Fermi energy variable [10, 11]:

$$F \equiv \frac{(\sqrt{s}_{NN} - 2m_N)^{3/4}}{\sqrt{s}_{NN}^{1/4}}, \tag{3}$$

where $\sqrt{s}_{NN}$ is the c.m. energy for a nucleon–nucleon pair and m_N is the nucleon mass. There are several advantages in using F as an energy variable. The measured mean pion multiplicity in N+N interactions is approximately proportional to F [12, 7]. In the Landau model [11] both the entropy and the temperature of the initially created matter (for $\sqrt{s}_{NN} \gg 2m_N$) are also proportional to F.

The 'entropy' presented in Fig. 2 is calculated as:

$$S \equiv \langle \pi \rangle + \kappa \langle K + \overline{K} \rangle + \alpha \langle N_P \rangle, \tag{4}$$

where the two last components take into account kaon production and pion absorption [7, 8]. Thus S can be treated as the inelastic entropy measured in pion entropy units.

The normalized 'entropy' for central A+A collisions at low energies (AGS and below) follows the dependence established by N+N data. It is about 30% higher for A+A collisions at SPS energies (the data of NA35 and NA49 Collab.) than for N+N interactions.

The energy dependence of the E_S ratio is also shown in Fig. 2. The results for N+N interactions are scaled by a factor of 3.6 to fit A+A data at AGS for a better comparison of the energy dependence. A monotonic increase of the E_S ratio between Dubna energy ($p_{LAB} = 4.5$ A·GeV/c) and SPS energies is observed. In the range from AGS to SPS the E_S ratio for N+N interactions is enhanced by a factor of about 2. A qualitatively different dependence is seen for central A+A collisions. An increase of E_S between Dubna† and AGS energies is followed by a weak (if any) change of E_S between AGS and SPS collision energies.

Let us now try to understand the observed energy dependence on a qualitative level. In the generalized Landau model [7] the inelastic entropy is given by:

$$S \sim g^{1/4} \langle N_P \rangle F, \tag{5}$$

where g is the effective number of degrees of freedom. Thus the observed deviation of the data for A+A collisions from the Landau scaling, $S/\langle N_P \rangle \sim F$, can be interprated as due to an increase of the effective number of degrees of freedom when crossing the transition collision energy. The magnitude of this increase can be estimated, within

† Note that the saturation of the E_S with $\langle N_P \rangle$ at Dubna energy is still not established experimentaly, see Fig. 1

the model, as the fourth power of the ratio of slopes of straight lines describing low and high energy A+A data: $1.33^4 \approx 3$ [7]. Note that this estimation can be treated as an upper limit as it is based on the assumption that the inelasticity is the same in the N+N and A+A collisions.

The second dominant effect of the transition to a QGP is the reduction of the effective masses of degrees of freedom. Basic thermodynamics tells us that for massless particles the ratio *(particle number)/entropy* is independent of the temperature. For massive particles the ratio increases with T at low temperature and approaches the saturation level (equal to the corresponding ratio for massless particles) at high temperatures, $T \gg m$. This property can be used to estimate the magnitude of the effective mass of strangeness carriers in strongly interacting matter. The E_S ratio is approximately proportional to the ratio *(number of strangeness carriers)/entropy (strangeness/entropy)* and therefore its temperature (collision energy, F) dependence should be sensitive to the effective mass of strangeness carriers. Reducing the mass of strangeness carriers should cause a weaker dependence of the E_S ratio on the collision energy. An increase of the E_S ratio in the energy range of $F < 2$ GeV$^{1/2}$ can be interpreted as due to the large effective mass of strangeness carriers (kaons or constituent strange quarks, $m_S \approx 500$ MeV/c^2) in comparison to the temperature of matter, $T < T_C \approx 150$ MeV. At temperatures above T_C, the matter is in the form of a QGP and the mass of strangeness carriers is equal to the mass of current strange quarks, $m_S \approx 150$ MeV/c^2, consequently $m_S \leq T$. Thus a much weaker dependence of the E_S ratio on F is expected in the high energy region where the creation of the QGP takes place. The equilibrium value of the *strangeness/entropy* ratio is higher in hadronic matter (HM) than in the QGP at very high temperatures [13]. This is due to the fact that it is proportional to the ratio of the effective number of strangeness degrees of freedom to the number of all degrees of freedom. This ratio is lower in a QGP than in HM. At low temperature, however, the *strangeness/entropy* ratio is lower in HM than in a QGP. This is caused, as previously discussed, by the high mass of strangeness carriers in HM. Thus, in general, a transition to the QGP may lead to an increase or a decrease of the *strangeness/entropy* ratio depending at which temperatures of the QGP and the HM the comparison is made.

The presented data suggest that the transition is associated with a decrease of the *strangeness/entropy* ratio. Thus one can expect a non–monotonic energy dependence of the *strangeness/pion* ratio; an initial increase of the ratio should be followed by a drop of this ratio to the characteristic value for the QGP. Above the transition region the ratio is expected to be collision energy independent.

4. Model of QGP in A+A

Encouraged by the qualitative agreement of the data with the hypothesis of the equilibrium QGP creation in the early stage of A+A collisions at SPS, we attempt to make a quantitative comparison using the simplest version of the generalized Landau model [7, 9]. In the first part of this section we formulate the model and compare the results with the experimental data. In the second part we critically review the basic assumption made.

4.1. Model Formulation and Results

We assume that inelastic energy (energy carried by the produced particles) is deposited and thermalized in a volume equal to the Lorentz contracted volume of the two overlapping nuclei (we only consider collisions of two identical nuclei only). In this volume an equilibrated QGP is formed. For simplicity, we assume that the two barionic fluids containing baryons of projectile and target nuclei are initially decoupled from the baryon–free QGP. Furthermore, we assume that the inelastic entropy† and strangeness are not changed during the system evolution.

The inelastic energy at SPS was measured to be (67±7)% of the available energy [14], the same for S+S and Pb+Pb collisions. It is also weakly dependent on the collision energy between AGS and SPS [15]. In the model we use an approximation of the uniform distribution of matter in the colliding nuclei. The radius of such an effective nucleus is calculated as:

$$R = r_0 \cdot A^{1/3} = (\frac{3A}{4\pi\overline{\rho}})^{1/3}, \tag{6}$$

where A is a nuclear mass number and $\overline{\rho}$ is an average nuclear density calculated using a parametrization of the nuclear density distribution as given in Ref. [16]. The resulting values of r_0 are 1.34 fm and 1.27 fm for S and Pb nuclei, respectively. The value of $r_0 = 1.3$ fm is used in the calculations. Similar r_0 values are obtained from the fits to the A+A inelastic cross section [17] using a hard sphere approximation.

The QGP is assumed to consist of massless gluons and massive u, d, and s quarks, and the corresponding antiquarks. The average mass of light quarks was taken to be 7.2 MeV [18]. The strange quark mass was taken to be 175±25 MeV [18], this mass is determined at an energy scale of 1 GeV. The conversion factor between the calculated entropy and the 'entropy' evaluated from the experimental data is taken to be 4 (entropy per pion at T ≈ 150 MeV). The conversion factor between total strangeness and strangeness measured by the sum of Λ and $K + \overline{K}$ yields is taken to be 1.36 according to the N+N data and a procedure developed in [19]. It should be stressed that the model formulated in the above way has no free parameters.

The resulting production of entropy and strangeness in the energy range 30–500 A·GeV is represented by dashed lines in Fig. 2. The agreement with the data is surprisingly good. The analysis suggests that plasma created at the SPS has an energy density of about 10 GeV/fm^3 and a temperature of about 280 MeV.

4.2. Discussion of Basic Assumptions

In the following we review basic model assumptions concerning the early stage volume in which thermalization takes place, the thermalized energy and the production of entropy and strangeness.

Early Stage Volume. It was Fermi [10] who for the first time introduced the Lorentz contracted initial volume of two overlapping protons as an early stage volume in which thermalization of the available energy occurs. This assumption was later taken by Landau and collaborators [11] in order to define initial conditions for the hydrodynamical expansion of matter created in A+A collisions. This volume can be treated as a maximum volume (no compression of colliding matter) in which all

---

† Strictly speaking a fraction (less than 5% at CERN SPS) of the inelastic entropy is absorbed by baryonic fluids in the later stages of the system evolution. A correction for this effect is applied, see Eq. 4.

incomming matter has a chance to be excited. For central collisions of nuclei as large as the S–nucleus and energies as high as CERN SPS energies the above volume is large enough to use a grand canonical approximation for entropy and strangeness production [20]. The volume is also large enough to be calculated from the initial geometrical volume of the nucleus (here the limitation is given by the longitudinal dimension). The effect of 'smearing' due to the uncertainty principle can be neglected.

Thermalized Energy. Fermi [10] and Landau [11] assumed that the full available energy in the c.m. system is thermalized in the early stage volume. Instantenous decay of this matter into final state hadrons was assumed by Fermi. Landau, following Pomeranchuk's suggestion [21], assumed that the matter before freeze–out undergoes a hydrodynamical expansion. Both models are in direct contradiction with the data. They predict that the rapidity distribution of nucleons is narrower than the one for pions (due to the mass difference) in contrary to the measured distributions in p+p and A+A collisions [14]. In addition they predict similar† rapidity distributions of baryons and antibaryons, but the data for p+p and A+A collisions show strong differences between Λ and $\overline{\Lambda}$ distributions [23, 24].

Based on this observation and guided by the partonic structure of the nucleon Pokorski and Van Hove [22] postulated that only gluons are stopped in high energy hadron–hadron interactions and their energy is used for particle production. The valence quarks are assumed to fly through. This picture was converted later into a 3–fluid hydrodynamical model by Katscher and collaborators [25].

This leads us to the generalization of the Landau model [7] assuming that only the energy of the produced particles (inelastic energy) is thermalized in the early stage volume. In the case of A+A collisions a fraction of the inelastic energy (entropy) can be absorbed by barionic fluids in the late stage of the expansion. Thus the final state inelastic energy (entropy) should be corrected for this effect as discussed in Refs. [7, 8].

Entropy Production. A crucial assumption which allows us to connect properties of the matter at the early stage is an assumption that the entropy is produced only during the very first non–equilibrium stage of the collision, and it remains constant in the expansion, hadronization and freeze–out stages. Isentropic expansion of strongly interacting matter was postulated first by Landau [11] on the base of qualitative arguments; at very high energy densities one expects much shorter mean free path than the size of the system. The influence of the hadronization on the entropy content depends on the nature of the hadronization process which remains still unclear [26, 27]. Recent studies indicate that entropy seems to be only weakly affected in the freeze–out stage [28, 29].

Strangeness Production. In the model it is assumed that the strangeness reaches its equilibrium value at the early stage and remains unchanged during expansion, hadronization and freeze–out. Equilibration of strangeness during the high temperature stage of the expansion in the case of the QGP creation may be expected due to the fact that the estimated strangeness equilibration time is comparable with the life time of the QGP [27]. Note that in the equilibrium QGP, due to the low mass of the strange quarks, isentropic expansion implies expansion with approximately constant strangeness content. Due to this fact it is not important for the final results at which stage of the QGP evolution the equilibration of strangeness takes place. The validity of the assumption that the strangeness remains constant in the hadronization

---

† Exact results depend on the freeze–out conditions assumed in the model.

stage depends (as in the case of the entropy) on the nature of this process. The production of strangeness at the freeze–out stage can be neglected due to a relatively large mass of strange hadrons and the requirement of strangeness conservation.

5. Summary and Conclusions

The experimental data on pion and strangeness production indicate:
– saturation of pion and strangeness production with the number of participant nucleons,
– change in the collision energy dependence taking place between 15 A·GeV/c and 160 A·GeV/c.
Within a statistical approach the observed behaviour can be qualitatively understood as due to:
– equilibration of entropy and strangeness in collisions of heavy nuclei,
– transition to a QGP occuring between AGS and SPS energies associated with the increase of the effective number of degrees of freedom.
These observations already hold for central S+S collisions, they are not unique to central Pb+Pb collisions.

A non–monotonic collision energy dependence of the *strangeness/pion* ratio is expected in the transition energy region.

The results at SPS energies are in surprisingly good agreement with the calculations done within the the generalized Landau model. The analysis suggests that the plasma created at the SPS may have a temperature of about 280 MeV (energy density of about 10 GeV/fm^3).

Experimental studies of central Pb+Pb collisions in the energy range 20–160 A·GeV are **urgently** needed in order to localize the threshold energy more precisely and to study the properties of the QCD phase transition.

Acknowledgements. I would like to thank Christian Bormann for the comments to the manuscript.

References

[1] J. C. Collins and M. J. Perry, Phys. Rev. Lett. **34** (1975) 151, E. V. Shuryak, Phys. Rep. **C61** (1980) 71 and **C115** (1984) 151.

[2] L. Van Hove, Phys. Lett. **B118** (1982) 138.

[3] P. Koch, B. Müller and J. Rafelski, Phys. Rep. **142** (1986) 321.

[4] M. Gaździcki and D. Röhrich, Z. Phys. **C65** (1995) 215.

[5] M. Gaździcki and D. Röhrich, Z. Phys. **C71** (1996) 55.

[6] M. Gaździcki, hep–ph/9606473, Heavy Ion Physics **4** (1996) 33.

[7] M. Gaździcki, Z. Phys. **C66** (1995) 659.

[8] M. Gaździcki, M. I. Gorenstein and St. Mrówczyński, Frankfurt University Preprint IKF–HENPG/6–96, nucl-th/9701013.

[9] M. Gaździcki, nucl–th/9701050, Proceedings of the International Workshop on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria, 13–18 January, 1997 Eds.: H. Feldmeier, J. Knoll, W. Nörenberg, J. Wambach, page 217.

[10] E. Fermi, Prog. Theor. Phys. **5** (1950) 570.

[11] L. D. Landau, Izv. Akad. Nauk SSSR, Ser. Fiz. **17** (1953) 51,
S. Z. Belenkij and L. D. Landau, Uspekhi Fiz. Nauk **56** (1955) 309.

[12] A. I. Golokhvastov, Dubna Report, JINR E2–89–364 (1989).

[13] J. Kapusta and A. Mekjan, Phys. Rev. **D33** (1986) 1304.

[14] J. Bächler et al., Phys. Rev. Lett. 72 (1994) 1419.

[15] H. Ströbele, in Proceedings of Quark Matter 96, note that the values of inelasticity for S+S and Pb+Pb collisions at SPS are plotted incorrectly [14].

[16] S. Daté, H. Sumiyoshi and M. Gyulassy, Phys. Rev. **D32** (1985) 619.

[17] M. Kh. Anikina et al., Dubna Report 1–82–553 (1982), E. O. Abdurakhimov et al., Z. Phys. **C5** (1980) 1, T. F. Hoang, B. Cork and H. J. Crawford, Z. Phys. **C29** (1985) 611, A. Bamberger et al., Phys. Lett. **205** (1988) 583.

[18] H. Leutwyler, Phys. Lett. **B378** (1996) 313.

[19] H. Białkowska, M. Gaździcki, W. Retyk and E. Skrzypczak, Z. Phys. **C55** (1992) 491.

[20] J. Rafelski and M. Danos, Phys. Lett. 97B (1980) 279.

[21] I. Ya. Pomeranchuk, Dokl. Akad. Nauk SSSR **78** (1951) 884.

[22] S. Pokorski and L. Van Hove, Acta Phys. Pol. **B5** (1974) 229 and L. Van Hove and S. Pokorski, Nucl. Phys. **B86** (1975) 243.

[23] M. Gaździcki and O. Hansen, Nucl. Phys. **A528** (1991) 754.

[24] T. Alber et al. (NA35 Collab.), **C64** (1994) 195.

[25] U. Katscher, D. H. Rischke, J. A. Maruhn, W. Greiner, I. N. Mishustin and L. M. Satarov, Z. Phys. **A346** (1993) 209.

[26] L. P. Csernai and I. N. Mishustin, Phys. Rev. Lett. **74** (1995) 5005.

[27] J. Rafelski, J. Letessier and A. Tounsi, Acta Phys. Pol. **B27** (1996) 1035.

[28] J. Sollfrank and U. Heinz, Phys. Lett. **B289** (1992) 132.

[29] S. Ochs and U. Heinz, Phys. Rev. **C54** (1996) 3199.

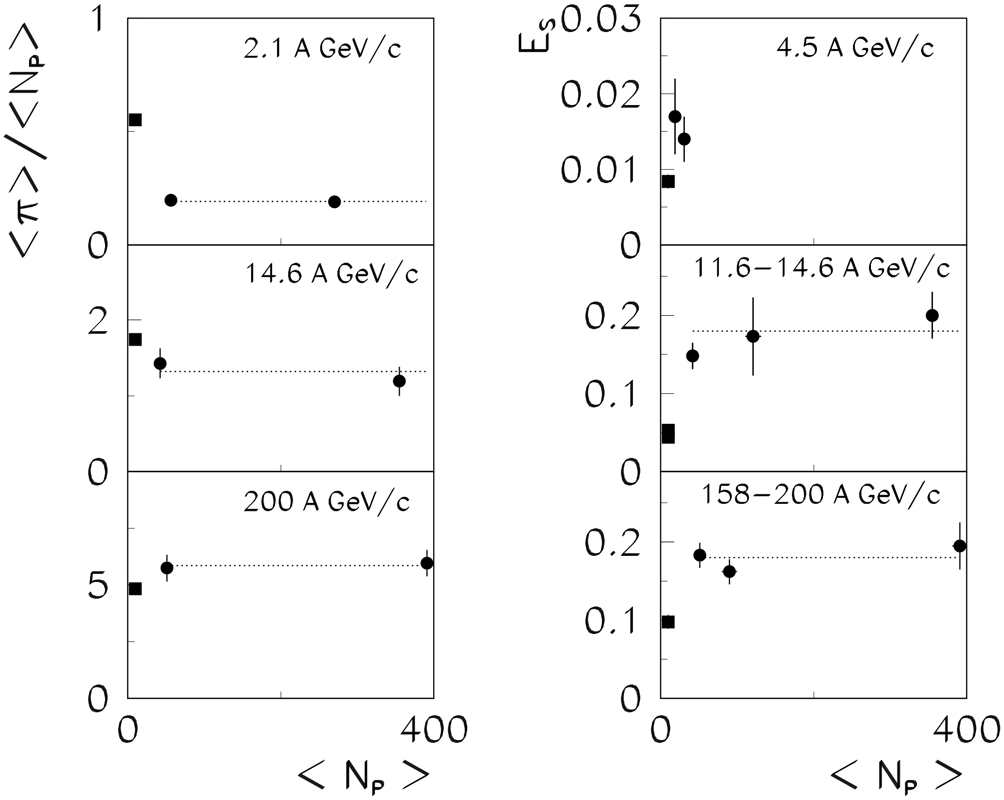

Figure 1. (left) The dependence of the ratio $\langle\pi\rangle/\langle N_P\rangle$ on $\langle N_P\rangle$ at three different collision energies. (right) The dependence of the E_S ratio on $\langle N_P\rangle$ at three different collision energies. The data for central A+A collisions are indicated by circles and the data for N+N interactions by squares.

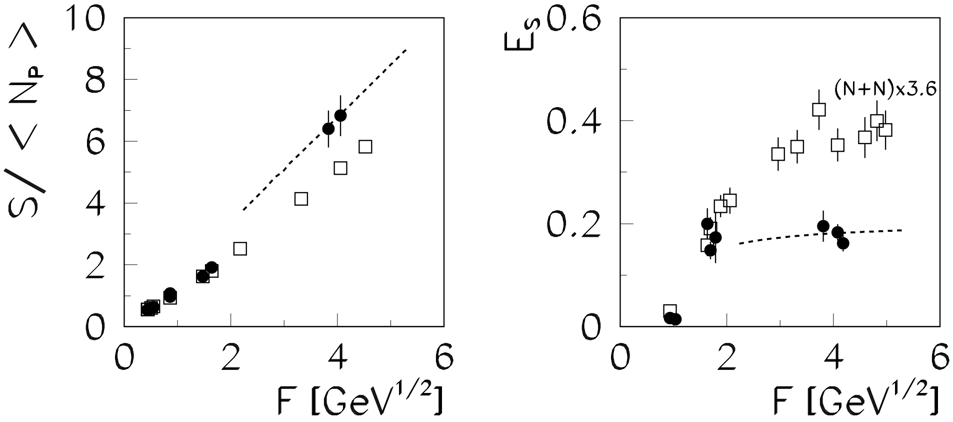

Figure 2. The dependence of $S/\langle N_P \rangle$ (left) and E_S (right) on the collision energy measured by the Fermi variable F. The data for central A+A collisions are indicated by circles and the data for N+N interactions by squares (the E_S values for N+N interactions are scaled by a factor of 3.6). The dashed lines show results obtained within the generalized Landau model assuming QGP creation.