Strangeness Excitation Function in Heavy Ion Collisions

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We study as function of energy strangeness created in relativistic heavy ion collisions. We consider statistical hadronization with chemical freeze-out in both equilibrium and nonequilibrium. We obtain strangeness per baryon and per entropy in the energy range $8.75 < \sqrt{s_{NN}} < 200$ A GeV. A baryon density independent evaluation of the kaon to pion ratio is presented.

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Production of strange hadrons in heavy ion collisions has been predicted to be sensitive to deconfinement. Firstly, there is the establishment by way of gluon fusion reaction $gg \rightarrow s\bar{s}$ of an abundant supply of strange quarks and antiquarks. Once the quark–gluon plasma (QGP) cools to the point of hadronization, in a second and independent step the final state hadrons are made in a recombination–fragmentation process [1]. A specific deconfinement feature is the enhanced production of strange antibaryons, increasing with strangeness content, a feature seen in recent experiments [2].

We analyze here experimental results in search for discontinuities in excitation of strangeness as function of reaction energy. The production yields of (strange) hadrons are studied in several experiments at the RHIC and at the SPS. Understanding of hadron yields in terms of phase space densities allows us to evaluate the global properties of all particles produced [3]. The particle production can be well described in a very large range of yields solely by evaluating the accessible phase space size, when including many hadron resonances [4].

In this work, we consider chemical equilibrium and non-equilibrium, i.e., we allow quark pair phase space occupancies, for light quarks $\gamma_q \neq 1$, and/or strange quarks $\gamma_s \neq 1$ [3] and we require balance of strange and anti-strange quark content [4]. There are two independent fit parameters when we assume complete chemical equilibrium, the chemical freeze-out temperature $T$ and $\mu_b$ the baryochemical potential (or equivalently, the quark fugacity $\lambda_q = e^{\mu_b/T}$). Adding the possibility that the number of strange quark pairs is not in chemical equilibrium, $\gamma_s \neq 1$, we have 3 parameters, and allowing also that light quark pair number is not in chemical equilibrium, we have 4 parameters. These three alternatives will be coded as open triangles (green online), open squares (violet) and filled squares (red), respectively, in the results we present graphically.

Statistical hadronization cannot be modeled completely today, as we neither know all hadron resonances, nor do we know the required branching ratios of resonance decays. This introduces arbitrariness in the model which can lead to discrepancies between hadronization analysis results. To estimate the systematic error, we have performed a study varying the pion yield artificially by a factor $0.8 < f_\pi < 1.2$. One can infer from this study that, if a relatively large hadronization temperature is reported, the presumption must be made that the statistical hadronization program used does not produce as many pions as required by an extrapolation of resonance mass spectrum and resonance decay pattern. Our computed yields have been cross-checked (for the chemical equilibrium variant) as noted in acknowledgments.

At RHIC, the baryon yield is found to contain many strange baryons. Not all results have been corrected for ensuing weak decays. We assume in our approach that 50% of weak decays from $\Xi$ to $\Lambda$ and from $\Omega$ to $\Xi$ are inadvertently included in the yields, when these had not been corrected for such decays. We further assume that pions from such weak decays are not included in the experimental yields, as these pions can clearly be shown to originate outside the interaction vertex.

We have carried out a RHIC-200 (i.e., $\sqrt{s_{NN}} = 200$ A GeV) Au–Au reaction analysis based on reported BRAHMS [8], PHENIX [10], PHOBOS [11], STAR [11], [12] results for $\pi$, $h^-$, $p$, $\bar{p}$, $K^\pm$, $K^*$, $\phi$, $\Omega$, $\Xi$ yields. We have further reanalyzed the extensive RHIC-130 Au–Au results (compare [13]) both in order to account for latest resonance yields and to make sure that there is no significant change introduced by the refinements made in the hadronization program. For the SPS, we take results obtained with Pb beams reacting with Pb stationary target at $\sqrt{s_{NN}} = 8.75, 12.25, 17.2$ GeV (projectile energy 40, 80, and 158 A GeV). We use here the SPS NA49-experiment $4\pi$ particle multiplicity results [14], which include $\pi^\pm$, $K^\pm$, $\Lambda$, $\bar{\Lambda}$, $\phi$ at 40, 80, 158 A GeV. We also fit (relative) yields of $\Xi$, $\bar{\Xi}$, $\Omega$, $\bar{\Omega}$ when available. Since we fit $4\pi$-particle yields, no information about the collective flow velocity is obtained.
TABLE I: The chemical freeze-out statistical parameters found for nonequilibrium (left) and semi equilibrium (right) fits to RHIC results. We show $\sqrt{s_{NN}}$, the temperature $T$, baryochemical potential $\mu_b$, strangeness chemical potential $\mu_S$, the quark occupancy parameters $\gamma_q$ and $\gamma_S/\gamma_q$, and the statistical significance of the fit. The star (*) indicates that there is an upper limit on the value of $\gamma_q^*$ at $e^{m_{\pi}/T}$ (on left), and/or that the value is set (on right).

| $\sqrt{s_{NN}}$ [GeV] | 200 | 130 | 200 | 130 |
|------------------------|-----|-----|-----|-----|
| $T$ [MeV]              | 143 ± 7 | 144 ± 3 | 160 ± 8 | 160 ± 4 |
| $\mu_b$ [MeV]          | 21.5 ± 1 | 29.2 ± 1.5 | 24.5 ± 1 | 31.4 ± 1.5 |
| $\mu_S$ [MeV]          | 4.7 ± 0.4 | 6.6 ± 0.4 | 5.3 ± 0.4 | 6.9 ± 0.4 |
| $\gamma_q$             | 1.6 ± 0.3* | 1.6 ± 0.2* | 1.4* | 1.4* |
| $\gamma_S/\gamma_q$   | 1.2 ± 0.15 | 1.3 ± 0.1 | 1.0 ± 0.1 | 1.13 ± 0.06 |
| $\chi^2$/dof           | 2.9/6 | 15.8/24 | 4.5/7 | 32.2/25 |

We present the RHIC freeze-out statistical parameters in table I. These results are incorporating statistical and systematic errors in the data, along with errors in the statistical hadronization theory, arising from the above described uncertainty of the pion yield. The bottom line in table I presents the statistical significance. The introduction of the full chemical nonequilibrium (on left) reduces by factor two the value of $\chi^2$. Even when allowing for all systematic uncertainties and theoretical uncertainty regarding the pion yield, the nonequilibrium fit is a more compelling considering the (presently) more data rich RHIC-130 system. The confidence level of the chemical equilibrium approach remains here at 15%. At RHIC-200, the current data can be interpreted within a chemical equilibrium model, since the decisive results on relative yields of (multi)strange (anti)hyperons are not yet available.

The statistical hadronization is expected to describe particle production well in presence of a sudden QGP breakup. Statisical hadronization approach is not appropriate when there is a lot of hadron–hadron rescattering in the final state, which may be the case at low SPS energies and below. In such case, kinetic models need to be applied, introducing a multitude of freeze-out conditions depending on the nature of particle considered. Accordingly, when we fit the low energy SPS results, a less favorable $\chi^2$ is found than at RHIC, or at the top SPS energy. However, the stability of the physical properties we extract when we subject the system to perturbations regarding pion yield indicate that results concerning the physical properties of the hadron source are reliable.

With the statistical parameters fixed, the properties of the fireball can be computed, evaluating the contributions made by each of the hadronic particle species. We first show how this works considering the energy stopping in figure 1. This result allows us to represent below our further findings as function of $E_{NN}^{th}$, the specific per baryon pair thermal energy available at the time of hadronization. This dependence substitutes for the dependence on $\sqrt{s_{NN}}$, the initial energy per baryon pair brought into the reaction. We see in figure 1 that the chemical equilibrium fit (open triangles) shows counter-intuitive behavior.

We note that the fraction of the energy per baryon pair which is initially thermalized is obtained from this result by adding the kinetic energy of the collective matter flow. Using at RHIC-200 as the average transverse flow velocity $v_T^2 = 0.45^2$ (and smaller values at smaller collision energies) we find a $\simeq 20\%$ correction. Thus, we see that $50 \pm 5\%$ of the energy per baryon carried into the reaction is initially made available to the thermal degrees of freedom, and this value is independent of the collision energy in the entire SPS and RHIC range $9 < \sqrt{s_{NN}} < 200$ GeV. This means that the baryon stopping is two times larger then energy stopping.

We are now ready to consider the final state specific per baryon strangeness yield. We evaluate strangeness yield $s$, the number of produced strange quark pairs and divide it by the similarly computed thermal fireball baryon number content $b$. $b$ is obtained summing the net (particle minus antiparticle) yields of all nucleons, (multi strange) hyperons and their resonances. The baryon number $b$ is naturally conserved. Strangeness is predominantly produced in the early stage of the reaction, when the density and temperature are highest, and there is little change in this yield during the late fireball evolution. Thus, $s/b$ ratio probes directly the extreme initial conditions. Consideration of this yield ratio eliminates the absolute yield normalization parameter (sometimes but not always ‘reaction’ volume), as well as some uncertainties originating in the experimental particle yield data, which propagate through the analysis of experimental data.

In figure 2 we show $s/b$ as function of the thermal specific energy content $E_{NN}^{th}$. Strangeness yield is continuous in the entire energy domain as is shown by the
solid line drawn to guide the eye. The rise of specific strangeness yield is slightly faster than linear with energy, as is indicated in the figure insert. (The appearance of an exponential shape is due to logarithmic energy scale in figure 2). The results for SPS energy range are in quantitative agreement with predictions made assuming a QGP state of matter and gluon fusion strangeness formation mechanism, compare figure 38 in Ref. 20. The SPS specific strangeness yield extrapolates smoothly to the RHIC energy range. The reaction mechanism producing strangeness and stopping baryon number are evolving in parallel yielding a smooth change in the ratio of both variables.

The highest energy $\sqrt{s_{NN}}=200$ GeV data point in figure 2 seems to be slightly lower than the presented extrapolation predicts. We think that this yield will increase once we have included in the statistical hadronization analysis the hyperon yield ratios $\Xi/\Lambda, \Lambda/p$. The presence, in the global fit, of these particle ratios will increase the fitted strangeness yield, provided that their measured values are comparable in magnitude to those reported at $\sqrt{s_{NN}}=130$ GeV.

An important feature of the RHIC experimental results, shown in figure 2, is the large strangeness yield per participating baryon. Although it has been early on noted that at RHIC-130, up to 8 strange quark pairs per baryon are produced 10, little attention has been given to this high yield. At RHIC-2000 each interacting baryon pair produces about 20 strange quark–antiquark pairs.

An interesting question is how this great increase in yield compares to the production of particles in general. The Wroblewski ratio $W_s \equiv 2 <s\bar{s}>/(u\bar{u}+d\bar{d})$ is often used in such a comparison. Recently it has been realized that this ratio can be artificially enhanced by high baryon density which can suppress light quark pair yields 10. Therefore we here compare the strangeness production to the global entropy $S$ yield. We evaluate $S$ in the same way as we have obtained other global properties. There is an additional nonequilibrium entropy term to be allowed for when chemical non-equilibrium prevails. Both entropy $S$ and strangeness $s$ are nearly conserved in the hydrodynamical expansion of QGP and increase only moderately in the hadronization of QGP. The observed ratio $s/S$ is established by microscopic reactions operational in the early stages of the heavy ion collision.

Strangeness per entropy, $s/S$, is presented in figure 3 as function of the specific thermal energy content. The horizontal line is the maximum SPS yield base. We note the modest smooth rise in the SPS energy domain. Most interestingly, at RHIC, as compared to SPS, an unexpected 50% increase in $s/S$ is noted, allowing for chemical nonequilibrium. The excitation of strangeness seems to rise faster with energy than the production of entropy. A possible explanation of this phenomenon is that the hot initial state, in which the threshold in energy for strangeness formation has been overcome, lives longer when formed at RHIC conditions. However, it appears important to fill the energy range between SPS and RHIC with data in search of a new physics energy threshold.

Based on the study of the $K^+ / \pi^+$ particle yield ratio 10, such a new physics energy threshold had been expected below 40A GeV, at the lowest SPS energy, i.e., below the energy range we could consider in the global hadron freeze-out analysis. Inspecting available particle yields, we note that their dependence on the unknown baryon density is significant, mimicking new physics. This baryon density effect can be greatly reduced considering the product of particle and antiparticle yields. In this case, the chemical potential cofactors in particle yields cancel, being inverse of each other, and the baryon density effect largely disappears. To study kaon to pion ratio we thus form: $K/\pi \equiv \sqrt{(K^+K^-)/(\pi^+\pi^-)}$, and effectively ‘remove’ baryon density effect present in the individual ratios $K^+/(\pi^+\pi^-)$ and $K^-/(\pi^+\pi^-)$. Using the NA49 data set 10, we present the $K/\pi$ ratio in figure 4. The filled squares are for the 4-π full phase space data set. The filled circles are for the central rapidity results, including RHIC-130 and RHIC-200 data 3. The central

![Figure 2](image1.png)  
**FIG. 2:** Strangeness per thermal baryon participant, $s/b$ as function of thermal specific energy content $E_{th}^{iNN}$.

![Figure 3](image2.png)  
**FIG. 3:** Strangeness per entropy, $s/S$, as function of the thermal specific energy content $E_{th}^{iNN}$.
FIG. 4: \( K/\pi \) ratio as function of collision energy. Filled symbols are for nuclear and open for \( K^+/\pi^+ \) measured in elementary pp collisions. Squares denote the full multiplicity ratio and circles the central rapidity yield ratio.

rapidity NA49 results are from figure 6 in [19]. The pp charged \( K^+/\pi^+ > K/\pi \) background is shown by open squares, and we indicate for \( \sqrt{s} = 1800 \) the \( p-\bar{p} \) TEVATRON point [21] which is at an energy beyond the range considered.

The lines, in figure 4, guide the eye to the trends of the alternate gradient synchrotron (AGS) and SPS results. These trends of behavior intersect within the SPS low energy range below the lowest NA49 SPS point which was obtained at 30 A GeV. However, this appears here to be a smooth transition from a rise to saturation of the \( K/\pi \) production. There is a clear enhancement of the \( K/\pi \) ratio at RHIC compared both with the AGS/SPS trend and with the \( K^+/\pi^+ > K/\pi \) measured in elementary pp collisions. This enhancement coincides with the specific strangeness per entropy, \( s/S \) enhancement seen in figure 3.

We have shown that the strangeness per baryon excitation in the fireball of dense matter formed at SPS and RHIC energies is a smooth function of energy, but we find a step-up in strangeness per entropy between the SPS and RHIC energy ranges, also visible in the rise of the \( K/\pi \) ratio. Thus there are two energy domains to investigate for threshold behavior, the 35+35 GeV RHIC range and the 20A GeV on fixed target low SPS energy, where the \( K/\pi \) ratio saturates. We further noted the quantitative agreement in the strangeness yield with predictions made for the SPS energy range, assuming QGP production mechanisms. We have shown that 20 strange–antistrange quark pairs are made per colliding baryon pair at the top RHIC energy.

Note added More technical details are now available in Ref. 22. A systematic study of SPS results by a yet another group has just appeared [23], and the numerical results shown there agree with our SPS results. Fig 10 shows that \( \gamma_q = 1 \) is actually a local fit maximum for the top SPS energy.

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