Strangeness enhancement
in the String Fusion Model Code

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Abstract

String Fusion Model Code results for Pb–Pb central collisions at SPS energies including the string fusion interaction mechanism are compared to the last experimental data. Predictions for RHIC energies are also presented.

On the other hand, the evolution of the strangeness enhancement ratio $E_s = \frac{\langle \Lambda \rangle + 4 \langle K^0_s \rangle}{3 \langle \pi^- \rangle}$ with the energy and with the atomic number of participant nuclei is discussed and related to the effects of string fusion and high–coloured strings.
1. Introduction: Strangeness enhancement has been proposed as a possible signal of the transition towards a deconfined phase, the so–called Quark Gluon Plasma (QGP) ([1, 2]). Using the String Fusion Model Code (SFMC, (3)) we have studied this effect for S–S and S–Ag central collisions at SPS energies ([4]).

In this paper we present the results obtained for Pb–Pb central collisions at $p_{lab} = 158$ GeV/c per nucleon and we compare them to the last experimental data.

We also study the evolution of the strangeness enhancement ratio $E_s = \frac{\langle \Lambda^+ + 4 < K^0_s > \rangle}{3 < \pi^- >}$ ([5]) with the energy and with the atomic number, and we propose other possible ratio to measure the strangeness, $E'_s = \frac{\langle \bar{\Lambda}^+ + 4 < K^0_s > \rangle}{3 < \pi^- >}$.

2. The String Fusion Model Code: Several string models like the Dual Parton Model (DPM, ([6])) or equivalently the Quark Gluon String Model (QGSM, ([7])) and models based on them like VENUS ([8]) have been very successful in describing particle production in hadron–hadron, hadron–nucleus and nucleus–nucleus interactions. Monte Carlo versions of these models ([3, 8, 9, 10]) are in reasonable agreement with most of the properties of soft multiparticle production.

However, the enhanced generation of strange particles ([11, 12, 13, 14, 15, 16]), in particular of strange antibaryons and $\phi$–mesons, that has been observed in the experiments at the CERN–SPS is not explained in the models quoted above.

These models have introduced different mechanism in order to reproduce that phenomenon. In this way, in the DPM the creation of sea diquark–antidiquarks pairs from the vacuum has been introduced, in addition to the usual quark–antiquark pairs ([17]), and in VENUS the fusion of particles and resonances into large clusters which decay isotropically ([18]) has been considered.
The String Fusion Model Code (SFMC, (3)) is a Monte Carlo code based on the QGSM that incorporates the possibility of string fusion. In this code, at high energy a hadron or nucleus collision is assumed to be an interaction between two clouds of partons, one from the projectile and the other from the target. Each parton–parton inelastic interaction leads to the creation of two colour strings. The strings have to be formed in pairs, with oppositely coloured fluxes, because the projectile and the target should remain colourless. We consider that the strings fuse when their transverse positions come within a certain interaction area, of the same order as parton–parton one. For present calculations it has been taken equal to 7.5 mb, and only fusion of strings in groups of 2 has been included. It is formally described by allowing partons to interact several times, the number of interactions being the same for projectile and target. The quantum numbers of the fused string are determined by the interacting partons and its energy–momentum is the sum of the energy–momenta of the ancestor strings. The colour charges of the fusing string ends sum into the colour charge of the resulting string ends according to the $SU(3)$ composition laws.

The breaking of the fused string is due to the production of two (anti)quark complexes with the same colour charges $Q$ and $\overline{Q}$ as those at the ends of the string. The probability rate is given by the Schwinger formula (19, 20, 21):

$$W \sim K^{2}_{[N]} e^{x \big( \frac{\pi M_{T}^{2}}{K_{[N]}} \big)} ,$$

where $K_{[N]}$ is the string tension for the $[N] SU(3)$ representation proportional to the corresponding quadratic Casimir operator $C^{2}_{[N]}$. In our case

$$C^{2}_{[3]} = 4/3, \quad C^{2}_{[6]} = 10/3, \quad C^{2}_{[8]} = 3 .$$
Therefore, the [8] and [6] fused strings have a higher string tension, giving rise to a larger heavy flavour production, in particular strangeness production.

The string fusion mechanism also produces a decrease of the mean number of strings. This leads to an overall reduction of multiplicities, specially of mesons.

On the other hand, the fused string decays into more diquarks and antidiquarks and into heavier quarks, so there will be an enhancement of strange particles, specifically of strange baryons and antibaryons.

3. Results: We have run our code in order to reproduce Pb–Pb central (impact parameter \( b \leq 2.8 \text{ fm} \)) collisions at \( p_{\text{lab}} = 158 \text{ GeV/c per nucleon} \).

Our results of negative charged particles, \( K_s^0 \) and protons for the string fusion case compared to experimental data ([22, 23]) are shown in Figure 1.

It is seen that our results for \( h^- \) are slightly higher than the experimental ones in the central region. For proton production we obtain a good agreement, specially when it is compared to other models predictions ([23]).

The experimental data on \( \Lambda \) and \( \bar{\Lambda} \) are not corrected for particles originating from \( \Xi \) and \( \bar{\Xi} \) decays, that in our code are taken into account separately. The possible correction due to these decays is close to 30% ([24]). So in order to compare the data on \( \Lambda \) and \( \bar{\Lambda} \) with our Monte Carlo results is necessary to take the first ones reduced in this proportion.

As we can see in Ref. [22], the mean number of \( \Lambda \) is around 10 times the one obtained for S–S central collisions, \( < \Lambda >_{\text{Pb–Pb}} = 10.5 \pm 3.7 < \Lambda >_{\text{S–S}} \). If we take the experimental value \( < \Lambda >_{\text{S–S}} = 9.4 \pm 1.0 \) and we correct it from \( \Xi \) and \( \bar{\Xi} \) contributions we obtain the approximate value \( < \Lambda >_{\text{Pb–Pb}} \sim 70 \) from experimental
data.

The experimental ratio $\bar{\Lambda}/\Lambda$ for Pb–Pb central collisions is $0.19 \pm 0.01$. We can calculate from this relation a mean multiplicity for $\bar{\Lambda}$ around 13, if $\Xi$ and $\Xi$ contributions are not included.

Relative to the SFMC results (string fusion included), we have obtained the values $<\Lambda> = 37.4$ and $<\bar{\Lambda}> = 10.5$.

It is observed that our result for $\Lambda$ is far away from experimental data, due to the fact that we don’t have rescattering or cascading mechanism in the code. One of the main effects of cascading will be an enhancement of $\Lambda$ production due to the processes:

$$\pi^- p(\pi^0 n) \rightarrow K^+ \Sigma^-, K^0 \Lambda; \quad \pi^+ n(\pi^0 p) \rightarrow K^+ \Sigma^0, K^+ \Lambda, K^0 \Sigma^+, \quad K^- p \rightarrow \pi^0 \Lambda,$$

$$\pi^+ \Sigma^-.$$  

For $\bar{\Lambda}$ the code result when the string fusion mechanism is included is close to the experimental one. Also, in the string fusion case we obtained the relation $<\bar{\Lambda}>_{\text{Pb–Pb}} = 10.5 <\bar{\Lambda}>_{\text{S–S}}$, while in the no fusion case this would be $<\bar{\Lambda}>_{\text{Pb–Pb}} = 5.5 <\bar{\Lambda}>_{\text{S–S}}$.

4. Strangeness enhancement: The ratio

$$E_s = \frac{<\Lambda> + 4 <K^0_s>}{3 <\pi^->}$$  \hspace{1cm} (3)

has been proposed in order to study the total production of strangeness in nucleus–nucleus collisions in a model independent way (13). For an isospin zero system this ratio is equivalent to the ratio

$$\frac{<\Lambda> + <K + \bar{K}>}{<\pi^->}.$$  \hspace{1cm} (4)
Our results for proton–proton and nucleus–nucleus collisions are shown in Figure 2 compared to experimental data. We can observed that for proton–proton collisions at SPS energies we obtain a value for $E_s$ much higher than the experimental one. This is due to the fact that for $\Lambda$ and $\bar{\Lambda}$ production, our results for proton–proton collisions at SPS energies both in the fusion and no fusion case are larger than the data because of the so–called delayed threshold effect (25). At these energies the cross section for $\Lambda$ and $\bar{\Lambda}$ production is rising very sharply, so small changes in the energy will lead to strong different results.

On the other hand, the mean number of strings created in a proton–proton collision is very small, so the probability for them to fuse is low. Because of this, the results don’t change from the no fusion to the fusion case. The string fusion effect grows with the energy and with the atomic number of participant nuclei. So for nucleus–nucleus collisions the fusion mechanism is more important and we find an enhancement of $E_s$, that is larger for Pb–Pb collisions.

Other possibility is to study the ratio

$$E_s' = \frac{\langle \bar{\Lambda} \rangle + 4 \langle K_0^0 \rangle}{3 \langle \pi^- \rangle}.$$  \hspace{1cm} (5)

The obtained results are presented in Figure 3. For Pb–Pb central collisions the experimental result coincides with the string fusion one.

The ratios $\bar{\Lambda}/\pi^-$ and $K_0^0/\pi^-$ are presented in Tables 1 and 2 for the fusion and no fusion case compared to experimental data. It is observed an enhancement of the ratio $\bar{\Lambda}/\pi^-$ from proton–proton to nucleus–nucleus collisions, that increases with the atomic number of participant nuclei. Nevertheless, for the experimental ratio $K_0^0/\pi^-$ there is only an enhancement from proton-proton to nucleus–nucleus collisions, but it doesn’t grow with the atomic number.
It seems that there is an increase of strange antibaryon production but not for strange meson one, which coincides with the code predictions. String fusion mechanism has two antagonistic effects on strange production: on one hand we have fused strings that decay into more strange particles, but on the other hand these strings decay mainly into baryons and antibaryons, so the overall dumping of multiplicities obtained as a consequence of the string fusion affects mostly to meson production.

Discussion and conclusions: It is important to take into account that in the SFMC only fusion of strings in pairs has been included.

Nevertheless the string fusion will be increased with the energy and the atomic number, because the density of strings grows, as can be seen in Table 3. So for Pb–Pb central collisions at SPS energies or for nucleus–nucleus collisions at RHIC energies it is necessary to consider the possibility to fuse the strings in bigger groups.

Even more, if the density of strings exceeds a critical value that can be calculate knowing the radius of each string (0.2 fm), percolation of strings becomes possible (26). The critical density necessary to have percolation is \( n_c = 9 \text{ strings/fm}^2 \). Above it paths of overlapping strings (circles in the transverse space, Figure 4) are formed through the whole collision area. Along these paths the medium behaves as a colour conductor.

The region where several strings fuse can be considered as a droplet of a non–thermalized QGP. Percolation means that these droplets overlap and QGP domain becomes comparable to nuclear size. This maybe a possible criterion for the existence of a deconfining phase.
It is important to take this possibility into account when studying the strangeness enhancement. In case of percolation the increase of strange particle production would compete with a strong reduction of multiplicities that would appear when many strings fuse into one and decay afterwards as an only string.

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References

[1] J. Rafelski and B. Müller, Phys. Rev. Lett. 48 (1982) 1066; 56 (1986) 2334E.

[2] J. Rafelski, Phys. Rep. 88 (1982) 331; Phys. Lett. B262 (1991) 333.

[3] N. S. Amelin, M. A. Braun and C. Pajares, Phys. Lett. B306 (1993) 312; Z. Phys. C63 (1994) 507.

[4] N. Armesto, M. A. Braun, E. G. Ferreiro and C. Pajares, Phys. Lett. B344 (1995) 301.

[5] M. Gazdzicki, NA35 Collaboration, Proceedings of the International Symposium on Strangeness and Quark Matter, Eds. G. Vassiliades, A. D. Panagiotou, S. Kumar and J. Madsen, World Scientific (1995) p. 72.

[6] A. Capella, U. P. Sukhatme, C.–I. Tan and J. Tran Thanh Van, Phys. Rep. 236 (1994) 225.

[7] A. B. Kaidalov and K. A. Ter–Martirosyan, Phys. Lett. B117 (1982) 247.
[8] K. Werner, Phys. Rep. **232** (1993) 87.

[9] H–J. Möhring and J. Ranft, Z. Phys. **C52** (1991) 643; I. Kawrakow, H. J. Möhring and J. Ranft, Z. Phys. **C56** (1992) 115.

[10] N. S. Amelin, L. P. Csernai, K. K. Gudina, V. N. Toneev and S. Yu. Sivoklolov, Phys. Rev. **D47** (1993) 1413.

[11] D. Röhrich, NA35 Collaboration, Nucl. Phys. **A566** (1994) 35c.

[12] E. Andersen et al., Phys. Lett. **B316** (1993) 603.

[13] S. Abatzis et al., Phys. Lett. **B270** (1991) 123.

[14] M. Gazdzicki, NA35 Collaboration, Nucl. Phys. **A566** (1994) 503c.

[15] R. M. Melo da Silva Ferreira, PhD. Thesis, Instituto Superior Tecnico, Lisbon (1993).

[16] C. Gerschel, in ”The Heart of Matter”, Rencontres de Blois, June 1994.

[17] J. Ranft, A. Capella and J. Tran Thanh Van, Phys. Lett. **B320** (1994) 346.

[18] K. Werner and J. Aichelin, Phys. Lett. **B308** (1993) 372.

[19] J. Schwinger, Phys. Rev. **82** (1951) 664.

[20] A. Casher, H. Neunberg and S. Nussinov, Phys. Rev. **D20** (1979) 179.

[21] M. Gyulassy and A. Iwazaki, Phys. Lett. **B165** (1985) 157.

[22] P. G. Jones, NA49 Collaboration, Nucl. Phys. **A610** (1996) 188c.

[23] N. Xu, NA44 Collaboration, Nucl. Phys. **A610** (1996) 175c.
[24] T. Alber et al., NA35 Collaboration, Z. Phys. C64 (1994) 195.

[25] A. Capella, U. P. Sukhatme, C.–I. Tan and J. Tran Thanh Van, Phys. Rev. D36 (1987) 109.

[26] N. Armesto, M. A. Braun, E. G. Ferreiro and C. Pajares, Phys. Rev. Lett. 77 (1996) 3736.
Table Captions

Table 1. Comparison between experimental data ([22, 23, 24]) and SFMC results of the ratio $\Lambda/\pi^-$ for p–p, S–S, S–Ag and Pb–Pb central collisions at SPS ($p_{lab} = 200$ AGeV/c for p–p, S–S, S–Ag collisions and $p_{lab} = 158$ AGeV/c for Pb–Pb collisions) and RHIC ($\sqrt{s} = 200$ AGeV) energies.

Table 2. Comparison between experimental data ([22, 23, 24]) and SFMC results of the ratio $K_0^0/\pi^-$ for p–p, S–S, S–Ag and Pb–Pb central collisions at SPS ($p_{lab} = 200$ AGeV/c for p–p, S–S, S–Ag collisions and $p_{lab} = 158$ AGeV/c for Pb–Pb collisions) and RHIC ($\sqrt{s} = 200$ AGeV) energies.

Table 3. Number of strings (upper numbers) and their densities ($\text{fm}^{-2}$) (lower numbers) in central p–p, S–S, S–U and Pb–Pb central collisions at SPS, RHIC and LHC energies.
Figure Captions

Figure 1. Rapidity distributions of $h^-$ (upper left figure), $K_s^0$ (upper right figure), $p$ (lower left figure) and transverse mass distribution of $h^-$ obtained with the SFMC code with string fusion and compared to experimental data (black squares) ([22, 23]) for Pb–Pb central collisions at $p_{lab} = 158$ AGeV/c.

Figure 2. Ratio $E_s = \frac{<\Lambda>+4<K^0>}{3<\pi^->}$ vs. the atomic number of the target nucleus for p–p, S–S, S–Ag and Pb–Pb central collisions at SPS (upper figure) and RHIC energies (lower figure). The black stars correspond to SFMC results in the fusion case, the empty stars correspond to SFMC results in the no fusion case and the points with error bars are the experimental data ([22, 23, 24]). For p–p collisions the same result is obtained for the no fusion and the fusion case.

Figure 3. Ratio $E'_s = \frac{<\Xi>+4<K^0>}{3<\pi^->}$ vs. the atomic number of the target nucleus for p–p, S–S, S–Ag and Pb–Pb central collisions at SPS (upper figure) and RHIC energies (lower figure). The black stars correspond to SFMC results in the fusion case, the empty stars correspond to SFMC results in the no fusion case and the points with error bars are the experimental data ([22, 23, 24]).

Figure 4. Strings in the transverse space. Each circle corresponds to one string.
Table 1

| Collision       | Experiment | Without fusion | With fusion |
|-----------------|------------|----------------|-------------|
| p–p at SPS      | 0.005      | 0.0088         | 0.012       |
| S–S at SPS      | 0.016      | 0.0055         | 0.013       |
| S–Ag at SPS     | 0.016      | 0.005          | 0.013       |
| Pb–Pb at SPS    | 0.020      | 0.004          | 0.019       |
| p–p at RHIC     |            | 0.0205         | 0.025       |
| S–S at RHIC     |            | 0.0185         | 0.028       |
| S–Ag at RHIC    |            | 0.0181         | 0.0285      |
| Pb–Pb at RHIC   |            | 0.0178         | 0.032       |
## Table 2

| Collision          | Experiment | Without fusion | With fusion |
|--------------------|------------|----------------|-------------|
| p–p at SPS         | 0.065      | 0.091          | 0.092       |
| S–S at SPS         | 0.11       | 0.091          | 0.101       |
| S–Ag at SPS        | 0.09       | 0.092          | 0.096       |
| Pb–Pb at SPS       | 0.11       | 0.93           | 0.11        |
| p–p at RHIC        | 0.10       | 0.10           |             |
| S–S at RHIC        | 0.10       | 0.12           |             |
| S–Ag at RHIC       | 0.10       | 0.12           |             |
| Pb–Pb at RHIC      | 0.10       | 0.13           |             |
| $\sqrt{s}$ (AGeV) | Collision |
|------------------|-----------|
|                  | p–p       | S–S       | S–U       | Pb–Pb     |
| 19.4             | 4.2       | 123       | 268       | 1145      |
|                  | 1.3       | 3.5       | 7.6       | 9.5       |
| 200              | 7.2       | 215       | 382       | 1703      |
|                  | 1.6       | 6.1       | 10.9      | 14.4      |
| 5500             | 13.1      | 380       | 645       | 3071      |
|                  | 2.0       | 10.9      | 18.3      | 25.6      |
Figure 1
Figure 2
a) Strings in the transverse space

b) Fused strings (in groups of 2 and 3 strings)

c) Percolation of strings: Paths of fused strings