Fast antibaryon production: A new collective effect in Pb–Pb collisions?

E. G. Ferreiro and C. Pajares

Departamento de Física de Partículas,
Universidade de Santiago de Compostela,
15706–Santiago de Compostela, Spain

Abstract

Recent experimental data on antibaryon production outside nucleon–nucleon kinematical limits have been obtained in Pb–Pb collisions at SPS energies. We present a possible explanation for this phenomenon based on the existence of collective effects. String Fusion Model results are compared to the data and predictions are also presented.

PACS numbers: 12.38.Mh, 25.75.-q, 13.87.Ce and 24.85.+p.
During the last year, new interesting effects have been shown by the recent data on Pb–Au and Pb–Pb collisions at $p_{\text{lab}} = 158$ GeV/c per nucleon. Increase of $e^+e^-$ pairs in the mass region of $0.3 \text{ GeV/c}^2 < m < 0.7 \text{ GeV/c}^2$ [1], strangeness enhancement [2] and a much larger $J/\psi$ suppression than in the case of S–U collisions [3] are some of these phenomena. Many papers have appeared on the physical origin of these effects, discussing mainly whether or not Quark Gluon Plasma (QGP) has been formed [4]–[11].

There is another part of the experimental data which, up to now, has not been paid enough attention. In fact, the NA52 Collaboration [12] has detected antiprotons outside of the kinematical limits of nucleon–nucleon collisions. The existence of particles above the nucleon–nucleon kinematical limit (particles with Feynman $x$ bigger than one) in Pb–Pb collisions, the well–known cumulative effect [13]–[16], was predicted to appear by the action of collective mechanisms [17], such as the string fusion or eventually the percolation of strings [8].

In this paper we compare our results with the data. First, we check that the String Fusion Model Code (SFMC, [18]) gives a reasonable description of other observables, like the multiplicity of negative charged particles or $\Lambda$ production in Pb–Pb collisions at SPS energies. In previous papers we have shown that the model describes reasonable well the hadron–hadron, hadron–nucleus and nucleus–nucleus existing data at similar energies, in particular the strangeness enhancement data [19] and the cumulative effect seen in hadron–nucleus collisions at 400 GeV/c [17].

In many models of hadronic collisions, like the Dual Parton Model (DPM, [20]) or equivalently the Quark Gluon String Model (QGSM, [21]) and models based on them like VENUS [22], colour strings are exchanged between projectile and target. The number of strings grows with the energy and with the number of nucleons of participant nuclei.

The String Fusion Model Code is a Monte Carlo code based on the QGSM that
incorporates the possibility of string fusion. When the density of strings becomes high, the string fields begin to overlap and eventually individual strings may fuse. 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. This value was previously fixed to describe the $\bar{\Lambda}$ production in S–S and S–Ag collisions \cite{19}. 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 strings ends sum into the colour charge of the resulting string ends according to the $SU(3)$ composition laws. The new strings break into hadrons according to their higher colour. As a result, heavy flavour is produced more efficiently and there is a reduction of the total multiplicity.

On the other hand, since the energy–momenta of the original strings are summed to obtain the energy–momentum of the resulting string, the fragmentation of the latter can produced some particles outside the kinematical limits of nucleon–nucleon collisions if the original strings come from different nucleon-nucleon collisions.

The code does not include other mechanisms like pop corn or cascading in spite of giving rise to non negligible effects. The reason is to distinguish the string fusion effects from the rest.

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

Our results of negative charged particles, $K^0_s$ and antilambdas for the string fusion case compared to the experimental data \cite{23, 24} are shown in Fig. 1.

It is seen that the SFMC results for $h^-$ are slightly higher than the experimental ones in the central region. A reasonable agreement is obtained for $K^0_s$ and $\bar{\Lambda}$ distributions, while for $\Lambda$ our result \cite{23} is lower than the experimental one, due to the fact that
we do not include the cascading mechanism in the code. It is very important for Λ production due to the processes:

\[ \pi^- p(\pi^0 n) \rightarrow K^+ \Sigma^-, \overline{K^0} \Lambda ; \quad \pi^+ n(\pi^0 p) \rightarrow K^+ \Sigma^0, K^+ \Lambda, \overline{K^0} \Sigma^+ \quad \text{and} \quad K^- p \rightarrow \pi^0 \Lambda, \pi^+ \Sigma^- . \]

Relative to the cumulative effect [13]–[17], in the string fusion approach it is naturally explained by the increased longitudinal momentum of the fused strings. String fusion picks up several partons coming from different nucleon–nucleon collisions so that particles with higher energy than the initial nucleon–nucleon one can be obtained.

In the string fusion picture, this can be understood as a process that takes place in two steps. The first step corresponds to the formation of 4 strings in 2 different nucleon–nucleon collisions, where 2 projectile nucleons and 2 target nucleons are involved. Each nucleon–nucleon collision leads to the creation of 2 colour strings. The energy of each collision is divided into the two formed strings in different fractions, \( x \) and \( x' \). So in one collision we will have 2 strings, whose total energy has to be \( x_1 + x'_1 = 1 \) (normalized to the total energy of the collision \( \sqrt{s_{NN}} \)), and \( x_2 + x'_2 = 1 \) for the 2 strings formed in the other collision. The second step arrives when the string fusion mechanism takes place. A fused string coming from 2 ancestor strings, each of them created in a different nucleon-nucleon collision, is formed. The energy–momentum of this new string is the sum of the energy–momenta of the elemental strings. The cumulative effect (\(|x_F| > 1\)) can happen when, by adding these energy-momenta, the total fraction of energy achieved by the fused string is bigger than one, \( x_1 + x_2 > 1 \).

Based on this idea, we propose the study of the cumulative production as a trail of the existence of collective effects.

In Fig. 2 our results for the antiproton rapidity distribution obtained with the SFMC are compared to the preliminary data of NA52. A very good agreement is found between the SFMC results for the string fusion case and the experimental data.

It is easy to calculate which is the \( x_F \) that corresponds to these antiprotons. These
particles, localized at $y = 6$ rapidity units and detected at $p_T = 0$, have a longitudinal momentum $p_z$ that can be calculated by using the well known relation between $y$ and $p_z$:

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}.$$  \hspace{1cm} (1)

The variable $x_F$ is defined in the center of mass frame. By applying the usual kinematic relations, it is possible to redefine it as a function of the laboratory frame variables. So we can express $x_F$ by:

$$x_F^{cm} = \frac{p_z^{cm}}{p_{beam}} = -(E_{lab}/m_2) + [(E_{beam} + m_2) p_{lab}^z/(m_2 p_{beam})] ,$$  \hspace{1cm} (2)

where $E_{lab}$ and $p_{lab}^z$ are the energy and longitudinal momentum of the particle in the laboratory frame, $m_2$ is the mass of the target and $E_{beam}$ and $p_{beam}$ are the energy and longitudinal momentum of the beam in the laboratory frame. As the energy and momentum of the beam are given per nucleon, then $m_2$ is the nucleon mass. So the Feynman $x$ corresponding to these antiprotons with $y = 6$ will be $x_F = 1.2$, well above the kinematical limits.

In Fig. 2 we also show the corresponding $x_F^{cm}$ distribution of those antiprotons. Fermi motion of the nucleons of the nucleus is included in the code, but the production of antibaryons at this rapidity cannot be explained without the inclusion of other collective effects. As can be seen in Fig. 2, the maximum rapidity attained by the antiprotons when the string fusion mechanism is not included (so only Fermi motion contributes) is $y = 5.5$, that corresponds to $x_F = 0.72$, far away from the kinematical limits.

The preceding results strongly support the idea about the intervention of a mechanism that permits to add energy coming from different nucleon-nucleon collisions, as the string fusion does. Other mechanisms of interaction of strings can also produce very fast particles [20].
On the other hand, in Fig. 3 our results on baryon production for Pb–Pb central collisions at SPS energy are shown. As we have said above, Fermi motion of the nucleons of the nucleus is included in the SFMC code. Because of this, some particles with $x_F > 1$ can also be obtained in the no fusion case, but its production is strongly increased by the introduction of the string fusion. The NA49 Collaboration is now analyzing data which could test this prediction. Concerning to the production of mesons with $x_F > 1$, in these collisions it is possible to obtain pions with $x_F = 1.5$ when the string fusion mechanism is included, while in the no fusion case the quantity of mesons found with $x_F$ bigger than one is negligible.

The results obtained for Pb–Pb central collisions at RHIC energies are similar to the ones got at SPS energies. For 1000 events, 2015 particles are produced with $|x_F| > 1$, to be compared to 1783 particles found at SPS energies. There is not a large increase of the cumulative effect from SPS to RHIC energies.

Nevertheless, it is important to take into account that in the SFMC only fusion of strings in pairs has been included. The string fusion effect increases with the energy and the atomic number of participant nuclei, because the density of strings grows, so the probability for them to fused becomes higher. Then 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 not only in pairs but in bigger groups. In that case, it would be possible to obtained particles with $x_F$ equal to three or even larger.

Even more, if the density of strings exceeds a critical value that can be calculate knowing the radius of each string (around 0.2 fm), percolation of strings becomes possible [8]. The critical density necessary to have percolation is about $n_c = 9$ strings/fm$^2$. Above it, paths of overlapping strings (that can be represented as circles in the transverse space) are formed through the whole collision area. Along these paths the medium
behaves as a colour conductor. This critical density is already reached in central Pb–Pb collisions at 158 AGeV/c and in central Ag–Ag collisions at RHIC energies [8].

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.

It is important to take this possibility into account when studying the cumulative effect. In case of percolation the possibility to obtain particles with \( x_F \) many times bigger than one would become no negligible.

More measurements of this effect in the actual Pb–Pb experiments and at RHIC will be welcome in order to clarify the existence of collective effects such as string fusion or eventually percolation of strings.

In conclusion we want to thank the CICYT and the Xunta de Galicia for financial support. We strongly thank to N. Armesto and M. A. Braun who participate in the earliest stage of this work.

References

[1] Th. Ullrich, CERES/NA45 Collaboration, Nucl. Phys. A610, 317c (1996).

[2] H. Helstrup, WA97 Collaboration, Nucl. Phys. A610, 165c (1996).

[3] M. Gonin, NA50 Collaboration, Nucl. Phys. A610, 404c (1996).

[4] C. M. Ko, G. Q. Li, G. E. Brown and H. Sorge, Nucl. Phys. A610, 342c (1996); G. Q. Li, C. M. Ko and G. E. Brown, Phys. Rev. Lett. 75, 4007 (1995); W. Cassing, W. Ehehalt and C. M. Ko, Phys. Lett. B363, 35 (1995).

[5] J. P. Blaizot and J. Y. Ollitrault, Phys. Rev. Lett. 77, 1703 (1996).

[6] D. Kharzeev and H. Satz, Phys. Lett. B336, 316 (1996).
[7] C.–Y. Wong, Nucl. Phys. A610, 434c (1996).

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

[9] S. Gavin and R. Vogt, Phys. Rev. Lett. 78, 1006 (1997).

[10] A. Capella, A. Kaidalov, A. Kouider Akil and C. Gerschel, Phys. Lett. B393, 431 (1997); N. Armesto and A. Capella, preprint LPTHE Orsay 97/11 (1997).

[11] H. Sorge, E. Shuryak and I. Zahed, preprint hep-ph/9705329 (1997).

[12] R. Klingerberg, NA52 Collaboration, Nucl. Phys. A610 306c, (1996); S. Kabana, NA52 Collaboration, Proceedings of the International Symposium on Strangeness and Quark Matter, Santorini, Greecce, April 1997. To appear in Journal of Physics G: Nuclear and Particle Physics.

[13] A. M. Baldin et al., Yad. Fiz. 20, 1210 (1974); Sov. J. Nucl. Phys. 20, 629 (1975).

[14] M. I. Strikman and L. L. Frankfurt, Phys. Rep. 76, 215 (1981).

[15] A. V. Efremov, A. B. Kaidalov, V. T. Kim, G. I. Lykasov and N. V. Slavin, Sov. J. Nucl. Phys. 47, 868 (1988).

[16] M. A. Braun and V. Vechermin, Nucl. Phys. B427, 614 (1994).

[17] N. Armesto, M. A. Braun, E. G. Ferreiro, C. Pajares and Yu. M. Shabelski, Phys. Lett. B389, 78 (1996); Astroparticle Physics 6, 329 (1997).

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

[19] N. Armesto, M. A. Braun, E. G. Ferreiro and C. Pajares, Phys. Lett. B344 (1995) 301.
[20] A. Capella, U. P. Sukhatme, C.–I. Tan and J. Tran Thanh Van, Phys. Rep. 236, 225 (1994).

[21] A. B. Kaidalov and K. A. Ter–Martirosyan, Phys. Lett. B117, 247 (1982).

[22] K. Werner, Phys. Rep. 232, 87 (1993).

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

[24] C. Borman, NA49 Collaboration, Proceedings of the International Symposium on Strangeness and Quark Matter, Santorini, Greece, April 1997. To appear in Journal of Physics G: Nuclear and Particle Physics.

[25] E. G. Ferreiro and C. Pajares, Proceedings of the International Symposium on Strangeness and Quark Matter, Santorini, Greece, April 1997. To appear in Journal of Physics G: Nuclear and Particle Physics.

[26] B. Andersson and P. Henning, Nucl. Phys. B355, 82 (1991).
Figure Captions

**Figure 1.** Rapidity distributions of $h^-$ (a), $K^0_s$ (b) and $\bar{\Lambda}$ (c) obtained with the SFMC code with string fusion and compared to experimental data (black squares) [23, 24] for Pb–Pb central ($b \leq 2.8$ fm) collisions at $p_{lab} = 158$ AGeV/c.

**Figure 2.** Rapidity distribution (a) and $|x_F|$ distribution (b) (taking into account both negative $x_F$ and positive $x_F$ contributions) of antiprotons around the kinematical limits for Pb–Pb collisions at 158 AGeV/c. The continuous line corresponds to the SFMC results with string fusion mechanism, the dashed line is the SFMC result without string fusion and the black squares are the experimental data points [12].

**Figure 3.** $x_F$ distributions for $x_F > 1$ in Pb–Pb central collisions at $p_{lab} = 200$ AGeV/c of protons (a) and $\Lambda$ (b) with (continuous line) and without (dashed line) string fusion.
Fig. 1

(a) $dN/dy$

(b) $dN/dy$

(c) $dN/dy$
Fig. 2

(a) $dN/dy$

(b) $|x_F| \times dN/dx_F$
