Overpopulation of $\Omega$ in pp collisions: a way to distinguish statistical hadronization from string dynamics

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The $\Omega/\Omega$ ratio originating from string decays is predicted to be larger than unity in proton proton interactions at SPS energies ($E_{\text{lab}}=160$ GeV). The anti-omega dominance increases with decreasing beam energy. This surprising behavior is caused by the combinatorics of quark-antiquark production in small and low-mass strings. Since this behavior is not found in a statistical description of hadron production in proton proton collisions, it may serve as a key observable to probe the hadronization mechanism in such collisions.

Hadron yields and their ratios stemming from the final state of ultra-relativistic heavy-ion collisions have been extensively used to explore the degree of chemical equilibrium and to search for evidence for exotic states and phase transitions in such collisions. Under the assumption of thermal and chemical equilibrium, fits with assumption of thermal and chemical equilibrium, fits with entropy. In fact, they are consistent with a model assuming the existence of equilibrated fireballs at a temperature $T \approx 160-170$ MeV. These findings have given renewed rise to the interpretation that hadronization in elementary hadron hadron (hh) collisions is a statistical process, which is difficult to reconcile with the popular picture that hadron production in hh collisions is due to the decay of color flux tubes, a model which has explained many dynamical features of these collisions.

In this letter we argue that the $\Omega/\Omega \equiv \Omega^-/\Omega^+$ ratio in elementary proton proton collisions is an unambiguous and sensitive probe to distinguish particle production via the break up of a color flux tube from statistical hadronization.

Color flux tubes, called strings, connect two SU(3) color charges [3] and [3] with a linear confining potential. If the excitation energy of the string is high enough it is allowed to decay via the Schwinger mechanism [3], i.e. the rate of newly produced quarks is given by:

$$\frac{dN_q}{dp_{\perp}} \sim \exp\left[-\pi m^2_{\perp}/\kappa\right],$$

where $\kappa$ is the string tension and $m_{\perp} = \sqrt{p_{\perp}^2 + m^2}$ is the transverse mass of the produced quark with mass $m$.

However, specific string models may differ in their philosophy and the types of strings that are created:

- In UrQMD [4] the projectile and target protons become excited objects due to the momentum transfer in the interaction. The resulting strings, with at most two strings being formed, are of the diquark quark type.
- In NeXuS [5], the pp interaction is described in terms of pomeron exchanges or ladder diagrams. Both hard and soft interactions take place in parallel. Energy is shared equally between all cut pomerons and the remnants. The endpoints of the cut pomerons (i.e. the endpoints of the strings) may be valence quarks, sea quarks or antiquarks.
- In PYTHIA [6], a scheme similar to that in UrQMD is employed. However, hard interactions may create additional strings from scattered gluons and sea quarks. Most strings are also of diquark quark form.

Fig. 1 (left) depicts the anti baryon to baryon ratio at midrapidity in proton proton interactions at 160 GeV. The results of the calculations by NeXuS, UrQMD and PYTHIA, which are well established string-fragmentation models for elementary hadron hadron interactions, are included in this figure. In all these models, the $\bar{B}/B$ ratio increases strongly with the strangeness content of the baryon. For strangeness $|s| = 3$ the ratio significantly exceeds unity. In UrQMD and PYTHIA the hadronization of the diquark quark strings leads directly
to the overpopulation of $\Omega$. In NeXuS, however, the imbalance of quarks and antiquarks in the initial state leads to the formation of $q_{\text{val}}-\bar{q}_{\text{sea}}$ strings (the $s_{\text{val}}-\bar{s}_{\text{sea}}$ string is not possible). These strings then result in the overpopulation of $\Omega$.

FIG. 1. Left: anti baryon to baryon ratio at $|y-y_{\text{cm}}| < 1$ in pp interactions at 160 GeV as given by PYTHIA, NeXuS and UrQMD. Right: anti baryon to baryon ratio for the same reaction as given by statistical models. Stars depict preliminary NA49 data for the $B/B$ ratio at midrapidity.

In Fig. 1 the model string results are compared with the predictions of statistical models (SM). Within the SM, hadron production is commonly described using the grand canonical (GC) partition function, where the charge conservation is controlled by the related chemical potential. In this description a net value of a given U(1) charge is conserved on average. However, in the limit of small particle multiplicities, conservation laws must be implemented exactly. This is done by using the canonical (C) ensemble. The conservation of quantum numbers in the canonical approach severely reduces the phase space available for particle production. Thus, exact charge conservation is of crucial importance in the description of particle yields in proton-induced processes and in $e^+e^-$, as well as in peripheral heavy-ion collisions.

In Fig. 1, the predictions of two different statistical models for $B/B$ ratios in pp collisions are included. The main difference between these models is the implementation of baryon number and electric charge conservation and the way an additional strangeness suppression is introduced.

The calculation in this statistical model is a full canonical one with fixed baryon number, strangeness and electric charge identical to those of the initial state. Also, an extra strangeness suppression is introduced to reproduce the experimental multiplicities. This is done by considering the number of newly produced $\langle s\bar{s} \rangle$ pairs as an additional charge to be found in the final hadrons. The $s\bar{s}$ pairs fluctuate according to a Poisson distribution and its mean number is considered as a free parameter to be fitted. The parameters used for the prediction of the $\Omega^+/\Omega^-$ ratio ($T$, global volume $V$ sum of single cluster volumes and $\langle s\bar{s} \rangle$) have been obtained by a fit to preliminary NA49 pp data yielding $T = 183.7 \pm 6.7$ MeV, $V T^3 = 6.49 \pm 1.33$ and $\langle s\bar{s} \rangle = 0.405 \pm 0.026$ with a $\chi^2$/dof = 11.7/9. It must be pointed out that the $\Omega^+$/\Omega^- ratio is actually independent of the $\langle s\bar{s} \rangle$ parameter and only depends on $T$ and $V$ (see also Fig. 1).

The conservation of baryon number and electric charge is approximated by using the GC ensemble. Under thermal conditions at top SPS energy this approximation leads to deviations from the exact C results in pp collisions by at most 20%–30%.

Strangeness conservation is, however, implemented on the canonical level following the procedure proposed in [18]. It accounts for strong correlations of produced strange particles due to constraints imposed by the locality of the conservation laws. In pp collisions strangeness is assumed not to be distributed in the whole volume of the fireball but to be locally strongly correlated. A correlation volume parameter $V_0 = 4\pi R_0^3/3$ is introduced, where $R_0 \sim 1$ fm is a typical scale of QCD interactions. The previous analysis of WA97 pA data yields: $R_0 \sim 1.12$ fm corresponding to $V_0 \approx 6$ fm$^3$. Note that, however, hidden strange particles are not canonically suppressed in this approach. The analysis of experimental data in AA collisions has shown that $T$ and $\mu_B$ are almost entirely determined by the collision energy and only depend weakly on the number of participants.

The $4\pi$ results of NA49 on $p/\pi$ and $\pi/A_{\text{part}}$ ratios in p-p and Pb-Pb collisions coincide within 20%–30%. In terms of the SM this can be understood if $T$ and $\mu_B$ are almost entirely determined by the collision energy and only depend weakly on the number of participants.

The predictions of the statistical models are shown in Fig. 1 (right). In these approaches the $B/B$ ratio is seen to exhibit a significantly weaker increase with the strangeness content of the baryon than expected in the string fragmentation models. For comparison, both figures include preliminary data on the $\Omega/B$ ratios obtained by the NA49 Collaboration.

| Model          | $\Omega$ ($\times 10^{-4}$) | $\Omega$ ($\times 10^{-4}$) |
|----------------|-----------------------------|-----------------------------|
| NeXuS          | 0.48                        | 0.79                        |
| PYTHIA         | 0.17                        | 0.30                        |
| UrQMD          | 0.66                        | 1.05                        |
| Canonical Model I | 0.46                     | 0.31                        |
| Canonical Model II | 0.41                     | 0.24                        |

TABLE I. Predictions of different models on the $4\pi$ yield of $\Omega$ and $\Omega$ in pp collisions at 160 GeV.
Note that the predictions of the statistical models in Fig. 1 refer to full phase-space particle yields whilst measurements of $\bar{B}/B$ ratios in pp collisions have been performed at midrapidity, where they are expected to be the largest. Therefore, sizeable deviations of the model results from the data seen in Fig. 1 are to be expected.

The rapidity density of $\Omega$ and $\Omega$ in pp interactions at 160 GeV as predicted by UrQMD, NeXuS, PYTHIA.

The rapidity dependence of the $\Omega$ and $\bar{\Omega}$ yield is presented in Fig. 2 within different string models. The results were calculated in pp interactions at 160 GeV within PYTHIA, NeXuS and UrQMD (from top to bottom). As can be seen, the $\bar{\Omega}/\Omega$ ratio is largest around mid rapidity.

The $\bar{\Omega}/\Omega$ ratio is fairly robust – different string-model implementations (PYTHIA, UrQMD, NeXuS) all agree in their predictions within $\pm 20\%$. However, as shown in Table 1 the total $4\pi$ yields of $\Omega$'s and $\bar{\Omega}$'s may differ by a factor of 4 between the different string models. The statistical models give in general more consistent results, however, deviations up to $30\%$ are not excluded. In string models, the particle abundances depend on the parameters chosen for the fragmentation scheme, while in statistical models they reflect the differences between the ensembles chosen. Thus, the absolute yields allow a distinction to be made between the implementations once experimental data become available. We will show now that this is a generic feature that string models give $\bar{\Omega}/\Omega > 1$, whereas statistical models yield $\bar{\Omega}/\Omega < 1$ in pp interactions.

In order to understand the large $\bar{\Omega}/\Omega$ values predicted by string models one elucidates in Fig. 3 the color flux tube break-up mechanism. Fig. 3 shows the fragmentation of the color field into quark-antiquark pairs, which then coalesces into hadrons. While in large strings $\Omega$'s and $\bar{\Omega}$'s are produced in equal abundance (a), low-mass strings in UrQMD suppress $\Omega$ production at the string ends (b), while in NeXuS $\bar{\Omega}$'s are enhanced (c). Thus, the microscopic method of hadronization leads to a strong imbalance in $\bar{\Omega}/\Omega$ ratio in low-mass strings.

The $\bar{\Omega}/\Omega$ ratio depends in a strongly non-linear fashion on the mass of the fragmenting string. Fig. 4 shows the $\bar{\Omega}/\Omega$ ratio as a function of the mass of the fragmenting string (i.e. different beam energies in pp). One clearly observes a strong enhancement of $\bar{\Omega}$ production at low energies, while for large string masses the ratio approaches the value of $\bar{\Omega}/\Omega = 1$ (which should be reached in the limit of an infinitely long color flux tube).

Statistical models, on the other hand, are not able to yield a ratio of $\bar{\Omega}/\Omega > 1$. This can be easily understood in the GC formalism, where the $\bar{B}/B$ ratio is very sensitive to the baryon chemical potential $\mu_B$. For finite baryon densities, the $\bar{B}/B$ ratio will always be $< 1$ and...
only in the limit of $\mu_B = 0$ may $\Omega/\Omega \rightarrow 1$ be approached. These features survive in the canonical framework, where the GC fugacities are replaced by ratios of partition functions $\frac{\Omega}{\Omega}$. This is shown in Fig. 4 (right) where the ratio $\Omega/\Omega$ in pp collisions (according to the previously described model $I$) is plotted as a function of volume for four different temperatures. Hence, finite size corrections in the statistical model actually lead to the opposite behavior $\frac{\Omega}{\Omega}$ in the ratio of $\Omega/\Omega$ vs. system size (i.e. volume replacing string mass) to that observed in the fragmenting color flux tube picture.

**FIG. 4.** Left: $\Omega/\Omega$ ratio as a function of string mass. Right: $\Omega/\Omega$ ratio as a function of the volume in model I.

In conclusion, within the fragmenting color flux tube models we have predicted that the $\Omega/\Omega$ ratio is significantly above unity. This is in strong contrast to statistical model results, which always imply that $\frac{\Omega}{\Omega}$ ratios are below or equal to unity in proton-proton reactions. Since this observable is accessible to NA49 measurements at the SPS it can provide an excellent test to distinguish the statistical model hadronization scenario from that of microscopic color-flux tube dynamics.

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[1] S. A. Bass, M. Gyulassy, H. Stöcker and W. Greiner, J. Phys. G25, R1 (1999); H. Satz, Rep. Prog. Phys. 63, 1511 (2000).
[2] H. Stöcker, W. Greiner and W. Scheid, Z. Phys. A286, 121 (1978);
D. Hahn and H. Stöcker, Nucl. Phys. A452, 723 (1986).
[3] R. Stock, Phys. Rep. 135, 261 (1986); Phys. Lett. B456, 277 (1999).
[4] J. Rafelski and B. Müller, Phys. Rev. Lett. 48, 1066 (1982); J. Rafelski, Phys. Rep. 88, 331 (1982); P. Koch, B. Müller and J. Rafelski, Phys. Rep. 142, 167 (1986).
[5] J. Letessier, A. Tounsi, U. Heinz, J. Sollfrank and J. Rafelski, Phys. Rev. Lett. 70, 3530 (1993); J. Letessier, J. Rafelski and A. Tounsi, Phys. Lett. B321, 394 (1994); J. Rafelski and M. Danos, Phys. Rev. C50, 1684 (1994).
[6] J. Cleymans and K. Redlich, Phys. Rev. Lett. 81, 5284 (1998); F. Becattini, J. Cleymans, A. Keranen, E. Suohonen and K. Redlich, Phys. Rev. C64, 024901 (2001).
[7] P. Braun-Munzinger, I. Heppke and J. Stachel, Phys. Lett. B465, 15 (1999).
[8] P. Braun-Munzinger, J. Stachel, J. P. Wessels and N. Xu, Phys. Lett. B344, 43 (1995); B365, 1 (1996); P. Braun-Munzinger and J. Stachel, Nucl. Phys. A606, 320 (1996); P. Braun-Munzinger, D. Magestro, K. Redlich and J. Stachel, Phys. Lett. B518, 41 (2001).
[9] C. Spieles, H. Stocker and C. Greiner, Eur. Phys. J. C2 351 (1998) 351; C. Greiner and H. Stöcker., Phys. Rev. D44, 3517 (1992). S. A. Bass et al., Phys. Rev. Lett. 81, 4092 (1998).
[10] R. Hagedorn, Nuovo Cim. Suppl. 3, 147 (1965); R. Hagedorn and J. Ranft, Nuovo Cim. Suppl. 6, 169 (1968).
[11] F. Becattini, Z. Phys. C69 (1996) 485; F. Becattini and U. Heinz, Z. Phys. C76, 269 (1997).
[12] A. Casher, H. Neuberger and S. Nussinov, Phys. Rev. D20, 179 (1979).
[13] J. S. Schwinger, Phys. Rev. 82 (1951) 664.
[14] M. Bleicher et al., J. Phys. G25 1859 (1999); S. A. Bass et al., Prog. Part. Nucl. Phys. 41 225 (1998).
[15] H.J. Drescher et al., Phys. Rep. 350 93 (2001).
[16] H.-U. Bengtsson and T. Sjöstrand, Comput. Phys. Commun. 46 43 (1987).
[17] R. Hagedorn, CERN Rep. 71 (1971); E. Shuryak, Phys. Lett. B42 357 (1972); J. Rafelski, Phys. Lett. B97 (1980) 279; K. Redlich and L. Turko, Z. Phys. C5, 201 (1980); C.M. Ko, V. Koch, Z. Lin, K. Redlich, M. Stephanov and X.N. Wang, Phys. Rev. Lett. 86, 5438 (2001); P. Braun-Munzinger, J. Cleymans, H. Oeschler and K. Redlich, hep-ph/0106066.
[18] J. S. Hamieh, K. Redlich and A. Tounsi, Phys. Lett. B486 61 (2000); J. Phys. G27, 413 (2001).
[19] R. Hagedorn, and K. Redlich, Z. Phys. C27, 541 (1985); J. Cleymans, K. Redlich and E. Suohonen, Z. Phys. C51, 137 (1991).
[20] F. Becattini and A. Keränen, to appear.
[21] M. Gorenstein and M. Gazdzicki, Phys. Lett. B483, 60 (2000).
[22] F. Becattini and G. Passaleva, hep-ph/0110312.
[23] J. Bachler et al., Nucl. Phys. A661 45 (1999); R.A. Bartron et al., J. Phys. G27 367 (2001); V. Afanasev et al., Phys. Lett. B491 59 (2000); M. Gazdzicki, priv. comm.