Hyperon yields in Pb-Pb collisions from NA57 experiment

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We report results from the experiment NA57 at CERN SPS on hyperon yields at midrapidity in Pb-Pb collisions at 158 A GeV/c and 40 A GeV/c. Λ, Ξ and Ω yields are compared with preliminary results from the STAR experiment at BNL.

1. Introduction

The NA57 experiment is part of the experimental program using ultra-relativistic heavy-ion beams at CERN SPS. This program aims at investigating the behaviour of hadronic matter under extreme conditions of temperature, pressure and energy density[1]. The assessment of the combined results of the CERN heavy-ion experiments suggests that a colour deconfined new state of matter is produced in central Pb-Pb collisions at 158 A GeV/c [2].

Several signatures have been proposed for the possible observation of a deconfined Quark-Gluon Plasma (QGP) in ultra-relativistic heavy-ion collisions; among them one of the first was the enhancement of the strangeness abundance in heavy-ion collisions with respect to nucleon-nucleon collisions[3]. NA57 has been designed to continue and extend the study, initiated by its predecessor WA97, on the production of strange and multistrange particles in Pb-Pb interactions at SPS energies.

The WA97 experiment had measured an enhanced production of strange and multi-strange baryons and anti-baryons in Pb-Pb interactions at 158 A GeV/c with respect to p-Be at the same energy. The enhancement is defined as the hyperon yield per wounded nucleon relative to p-Be:

$$E = \left(\frac{\langle Yield \rangle}{\langle N_{\mathrm{wound}} \rangle} \right)_{Pb-Pb} / \left(\frac{\langle Yield \rangle}{\langle N_{\mathrm{wound}} \rangle} \right)_{p-Be} \tag{1}$$

where the wounded nucleons are those nucleons both from projectile and target taking part in the primary nucleon-nucleon collision.

Figure 1 shows the WA97 results on the hyperon enhancements per unit of rapidity at midrapidity in Pb-Pb collisions at 158 A GeV/c as a function of the number of wounded nucleons. While the hyperon yields per wounded nucleon have similar values in p-Be and p-Pb collisions, they are found to be enhanced when going from p-A to Pb-Pb collisions. The horizontal line at 1 points out where Pb-Pb yields would have been in case of no enhancement. In particular, the enhancement increases with the strangeness content of the hyperon: Ωs are more enhanced than Ξs and Ξs are more enhanced than Λs[4]. This pattern of hyperon abundances can be easily explained in a colour deconfined scenario such as QGP, while it contradicts the expectations from rescattering in the hadronic fireball. In fact, multistrange particle formation would be hindered in the hadron gas by high thresholds (e.g.: the threshold for the reaction $\pi^+ + \pi^- \to \Omega^- + \overline{\Omega}^+$ is about 3 GeV) and low cross-sections.

In order to extend the study initiated by WA97, NA57 has taken data at two beam momenta: 158 A GeV/c and 40 A GeV/c . Special efforts were made in NA57 to enlarge, with respect to WA97, the triggered fraction of total inelastic cross-section thus extending the centrality range towards less central collisions. In this paper we report results on Ξ and Ω yields in Pb-Pb both at 158 and 40 A GeV/c and Λ yield at 158 A GeV/c . These results are then compared with some preliminary available results from STAR experiment at RHIC.

In Section 2 the NA57 apparatus is briefly described and the samples of data collected are summarized. Section 3 is dedicated to the determination of the collision centrality. In Section 4 the results on the strange hyperon production are presented: Section 4.1 deals

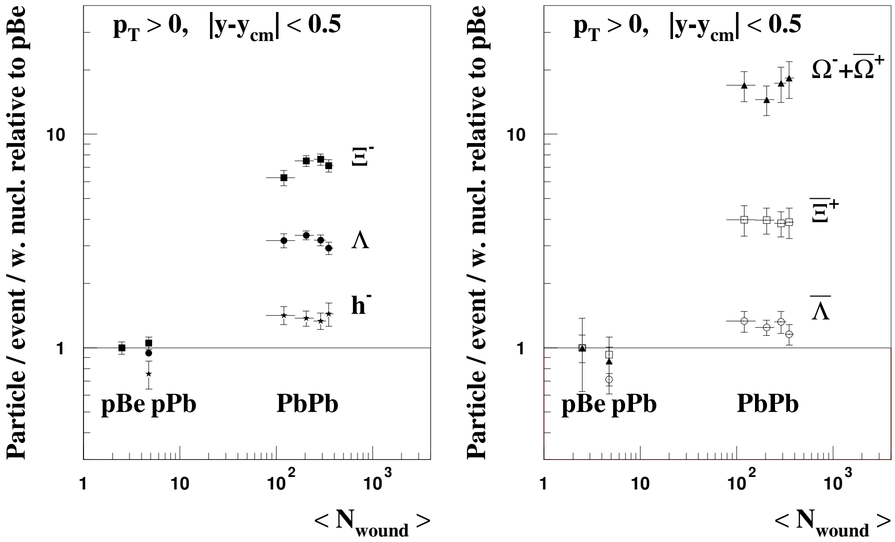

Figure 1. Yields per wounded nucleon per unit of rapidity at central rapidity relative to p-Be as a function of the number of wounded nucleons from WA97 experiment.

with the hyperon yields in Pb-Pb at 158 A GeV/c over the full NA57 centrality range; Section 4.2 deals with the energy dependence of the hyperon yields, in particular, the first results at 40 A GeV/c are reported. In this section the NA57 results at both energies are compared with preliminary results from STAR experiment. Section 5 presents conclusions and an outlook on the possible future programme of the NA57 experiment.

2. Experimental apparatus and Data sets

A detailed description of the NA57 apparatus, schematically shown in Figure 2, can be found in [5]. To face the challenge of handling the large density of tracks produced in central Pb-Pb interactions, we use a telescope made of high granularity bidimensional silicon pixel planes as tracking device. The high rate capability of silicon pixel detectors allows us to collect large statistics in order to study rare signals such as multi-strange hyperons. To improve the momentum resolution of high momentum tracks an array of double-sided silicon microstrip detectors is placed downstream of the tracking telescope.

The whole silicon telescope is placed above the beam line, inclined and aligned with the lower edge of the detectors laying on a line pointing back to the target. The telescope accepts particles produced at mid-rapidity and medium transverse momentum. The inclination angle α and the distance d of the first pixel plane from the target (see Figure 2) are varied with the beam momentum so as to cover about one unit of rapidity around central rapidity, namely: at 158 A GeV/c ($y_{CM}\simeq 2.9$) $\alpha = 40$ mrad and d = 60 cm, at 40 A GeV/c ($y_{CM} \simeq 2.2$) $\alpha = 72$ mrad and d = 40 cm.

Hyperons are identified via weak decay channels with only charged particles in the final state, namely

$$\Lambda \rightarrow \mathrm{p} + \pi^- \qquad \Xi^- \rightarrow \Lambda + \pi^- \;(\Lambda \hookrightarrow \mathrm{p} + \pi^-) \qquad \Omega^- \rightarrow \Lambda + \mathrm{K}^- \;(\Lambda \hookrightarrow \mathrm{p} + \pi^-)$$

and their charge conjugate decays.

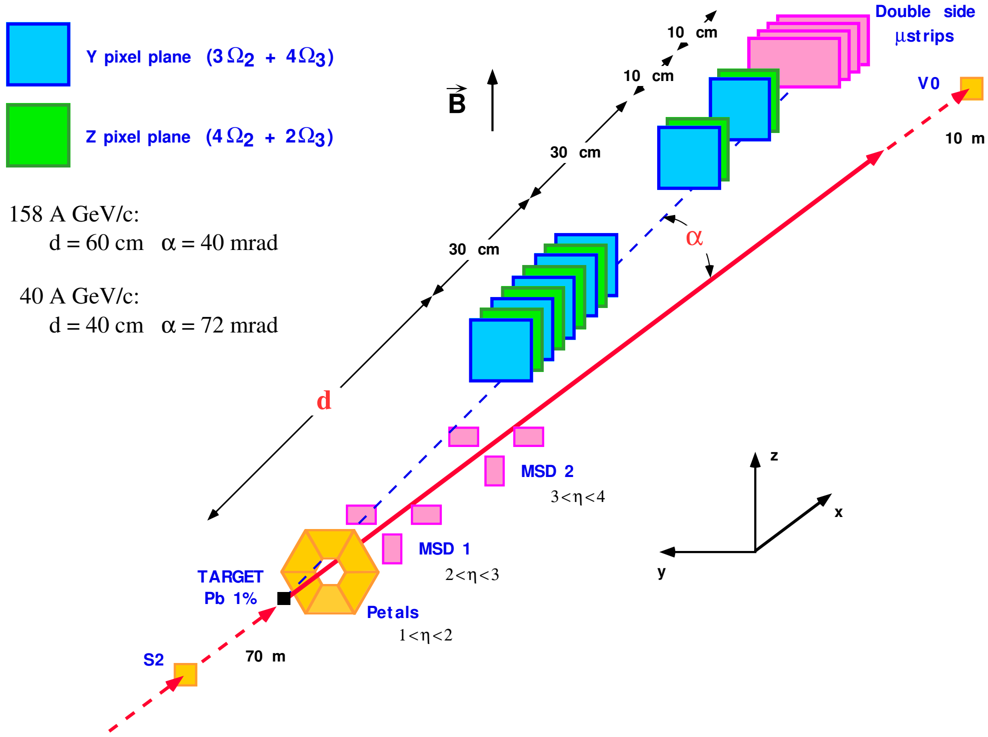

Figure 2. A sketch of the NA57 set up placed inside GOLIATH magnet.

As an example of the quality of the NA57 data, the invariant mass spectra for pπ, $\Lambda\pi$ and ΛK after all analysis cuts in Pb-Pb both at 158 A GeV/c and at 40 A GeV/c are shown in Figures 3 and 4. In all cases hyperon peaks are well centered at the PDG value with very low combinatorial background.

The centrality selection is based on a fast trigger signal provided by an array of 6 scintillator petals, placed 10 cm downstream of the target and covering the pseudorapidity region $1 < \eta < 2$.

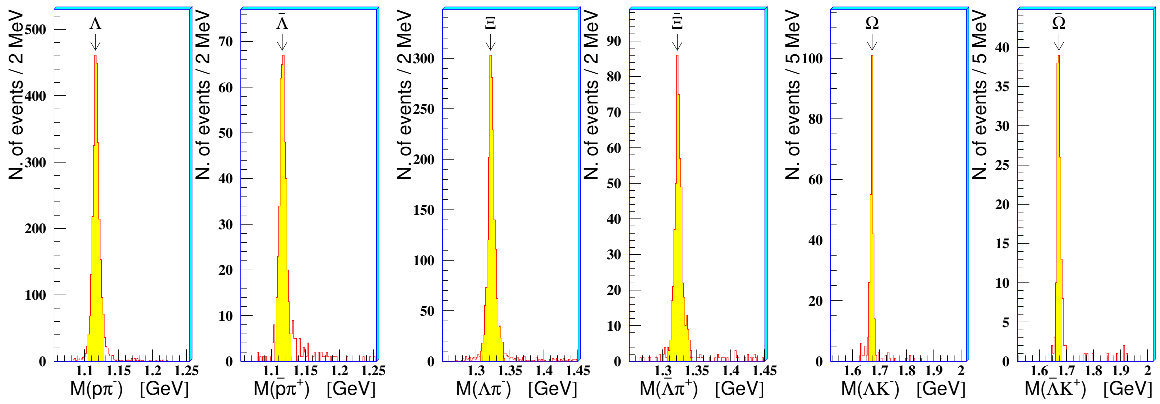

Figure 3. Invariant mass spectra for pπ, $\Lambda\pi$ and ΛK in Pb-Pb collisions at 158 A GeV/c.

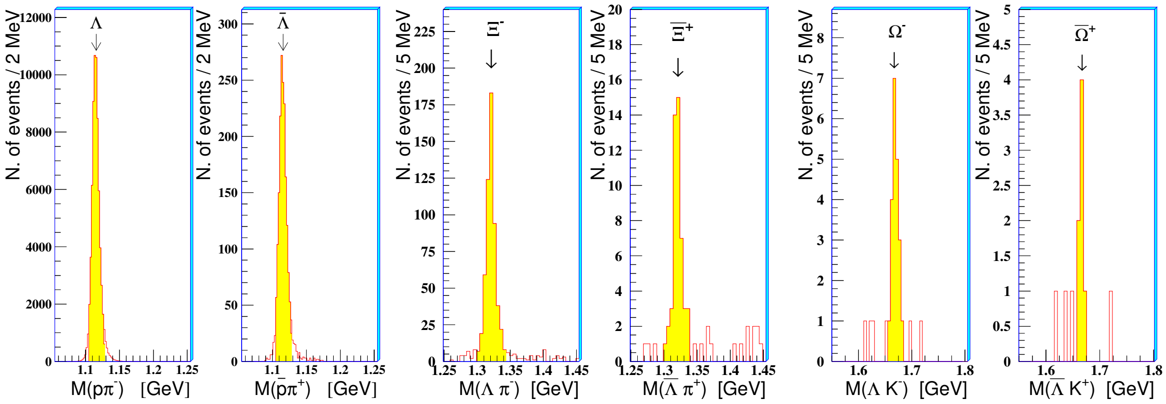

Figure 4. Invariant mass spectra for pπ, $\Lambda\pi$ and ΛK in Pb-Pb collisions at 40 A GeV/c.

NA57 has collected Pb-Pb data both at 158 and 40 A GeV/c beam momentum. In order to establish whether at these energies multi-strange particle production is enhanced in Pb-Pb interactions with respect to elementary hadronic interactions, p-Be reference data are necessary, this system being the best feasible approximation of nucleon-nucleon collisions. NA57 has collected p-Be data at 40 GeV/c, while as reference data at 158 GeV/c we use the p-Be set of data available from the WA97 experiment. In Table 1 the data sets collected by NA57 are summarized.

Table 1
Data sets collected from NA57.

System	Beam momentum	Sample size	Data taking
Pb-Pb	158 A GeV/c	230 M events	November 1998
p-Be	40 GeV/c	60 M events	July 1999
Pb-Pb	40 A GeV/c	240 M events	November 1999
Pb-Pb	158 A GeV/c	230 M events	October 2000
p-Be	40 GeV/c	110 M events	September 2001

3. Collision centrality

For a given colliding system and beam energy the collision centrality determines the volume and the energy of the fireball. The charged particle multiplicity is used in NA57 to define the geometry of the collision via the Glauber model [6].

Figure 5 shows the charged particle multiplicity distributions in Pb-Pb collisions at 158 A GeV/c (left) and 40 A GeV/c (right). At both energies the triggered fraction of the total nuclear inelastic cross section is about 60%.

At 158 A GeV/c the multiplicity distribution is divided in five centrality classes. The average number of wounded nucleons $\langle N_{wound}\rangle$ in each multiplicity class is determined

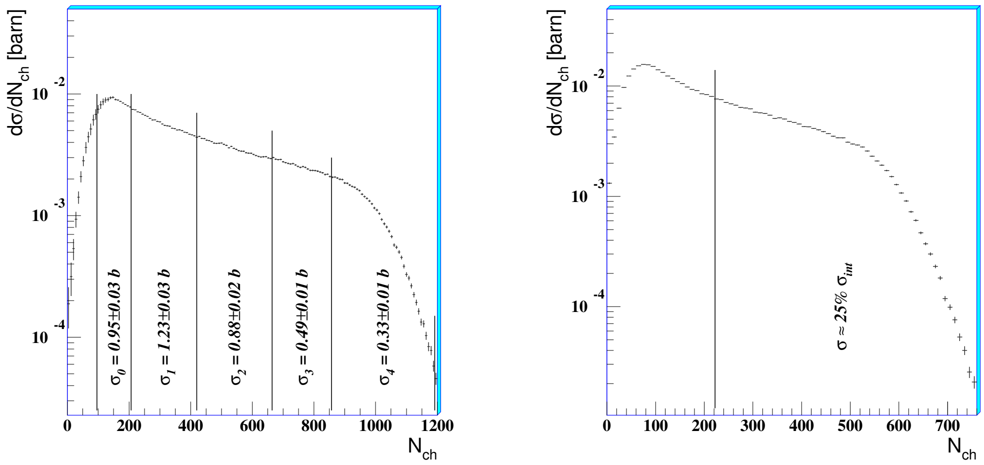

Figure 5. Charged particle multiplicity distribution in Pb-Pb at 158 A GeV/c (left) and 40 A GeV/c (right). The multiplicity classes used in the analysis are shown together with the corresponding cross section.

from the corresponding N_{wound} distribution computed from the trigger cross section [7].

As can be seen in Figure 5, the first multiplicity bin is the only one affected by the centrality trigger; for this bin a trigger efficiency has been calculated and accounted for. The average values of N_{wound} in each multiplicity class for Pb-Pb and in p-Be are listed in the second row of Table 2.

At 40 A GeV/c, the results on hyperon yields are given for a single centrality class corresponding approximately to the 25% most central Pb-Pb collisions, equivalent to the three most central classes at 158 A GeV/c . The average number of wounded nucleons for this sample is $\langle\ N_{wound}\ \rangle = 262 \pm 17$. When the study of the collision centrality will be completed, the results on hyperon yields will be binned in classes of centrality.

4. Hyperon yields

For each particle species we determine the number of particles per event, i.e. the yield, per unit of rapidity at central rapidity. Data are corrected for geometrical acceptance and for detector and reconstruction efficiencies. For each reconstructed Λ, Ξ and Ω particle a weight is calculated by a GEANT-based Monte Carlo procedure on an event-by-event basis [8]. For each particle a sample of hyperon decays are generated with the same measured y, p_T and the primary vertex position generated randomly according to its experimental distribution. The decay tracks are traced through a detailed simulation of the apparatus, where silicon pixel detector efficiencies are accounted for chip-by-chip. The hits of the decay tracks are merged with those of a true event. The merged event is then processed through the standard NA57 reconstruction and analysis chain. The weight associated to the real particle is calculated as the ratio of the number of Monte Carlo generated events to the number of Monte Carlo events successfully reconstructed and retained by all analysis selections.

All yields are extrapolated to a common phase space window covering full p_T and one unit of rapidity centered at midrapidity [9]:

$$Yield = \int_{m}^{\infty} \mathrm{d}m_T \int_{y_{cm}-0.5}^{y_{cm}+0.5} \mathrm{d}y \frac{\mathrm{d}^2 N}{\mathrm{d}m_T \mathrm{d}y} \qquad (2)$$

where y is the rapidity and m_T the transverse mass ($\sqrt{m^2+p_T^2}$).

4.1. Centrality dependence at 158 A GeV/c

The Pb-Pb sample of data is divided into 5 multiplicity classes, as described in Section 3. The yields per wounded nucleon relative to p-Be of Λ, Ξ, Ω and their anti-particles are plotted in Figure 6 as a function of the number of wounded nucleons. The p-Be and p-Pb results are those published by WA97. The measured particles are divided in two classes: those with at least one valence quark in common with the nucleon (left) and those with no valence quark in common with the nucleon (right). The two classes are kept separate since it is known that they may exhibit different production features, e.g. in the rapidity spectra.

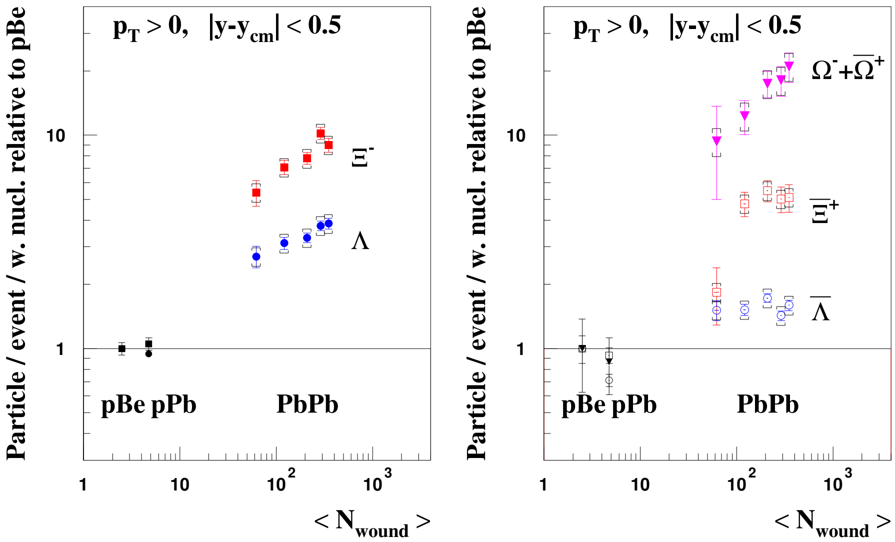

Figure 6. Hyperon yields per wounded nucleon in one unit of rapidity at central rapidity relative to p-Be as a function of the number of wounded nucleons. The symbol ⌷ indicates the systematic error.

The pattern of strangeness enhancements observed by WA97 is confirmed by NA57: Ωs are more enhanced than Ξs, which are more enhanced than Λs when going from p-Be to Pb-Pb data, up to a factor $\approx$20 for $\Omega^-+\overline{\Omega}^+$ in the most central class.

In the common centrality range, the yields from NA57 and WA97 agree within 20-30%. The difference has been extensively investigated [10]. The bulk of it has been understood as due to a bias introduced by the treatment of the uncertainty in the position of the primary vertex in WA97 (this bias has not affected the WA97 p-Be data). The outcome of this study gives us confidence in the NA57 results.

From Figure 6 one can see that the values of all particle yields per wounded nucleon, except those of the $\overline{\Lambda}$, increase within the Pb-Pb sample with the number of wounded nucleons. The $\overline{\Xi}^+$ yield shows a significant drop in the most peripheral class: going from $< N_{wound} > = 121$ to $< N_{wound} > = 62$ the yield decreases by a factor 2.6, corresponding to a 3.5 σ effect. The Ξ^- and $\overline{\Xi}^+$ statistics will be doubled when the ongoing analysis of the year 2000 data sample will be completed.

In Table 2 the hyperon yields in each centrality class are listed. The quoted errors are statistical only. We have estimated a systematic uncertainty on the enhancements of about 10% for Λ and Ξ and 15% for Ω^-+$\overline{\Omega}^+$.

Table 2
Hyperon yields at 158 A GeV/c in p-Be, p-Pb and in the five Pb-Pb centrality classes. Quoted errors are statistical only; the systematic errors are estimated to be about 10% for Λ and Ξ, about 15% for Ω^-+$\overline{\Omega}^+$.

	p-Be (WA97)	**p-Pb (WA97)**	**Pb-Pb (NA57)**				
class			0	1	2	3	4
$\langle N_{wound} \rangle$	2.5	4.75	62±4	121±4	209±3	290±2	349±1
Λ	0.0344±0.0005	0.060±0.002	2.30±0.22	5.19±0.29	9.5±0.5	15.0±0.8	18.5±1.1
$\overline{\Lambda}$	0.0111±0.0002	0.015±0.001	0.417±0.035	0.82±0.04	1.60±0.07	1.84±0.10	2.47±0.14
Ξ^-	0.0015±0.0001	0.0030±0.0002	0.200±0.024	0.51±0.04	0.98±0.06	1.78±0.11	1.88±0.14
$\overline{\Xi}^+$	0.00068±0.0001	0.0012±0.0001	0.031±0.009	0.16±0.02	0.31±0.04	0.40±0.05	0.48±0.07
Ω^-+$\overline{\Omega}^+$	0.00016±0.00006	0.000263±0.000078	0.037±0.017	0.095±0.017	0.23±0.03	0.33±0.05	0.47±0.07

4.2. Energy dependence

First results on Ξ and Ω yields in Pb-Pb collisions at 40 A GeV/c have been presented in a dedicated contribution to this Conference [11]. The particle yields shown in Table 3 are based on the ≈25% most central Pb-Pb collisions, with an average number of wounded nucleons $\langle N_{wound} \rangle = 262 \pm 17$. The quoted errors are statistical only, the systematic errors are similar to those at 158 A GeV/c.

Table 3
Ξ and Ω yields in Pb-Pb interactions at 40 A GeV/c; these results are based on approximately 25% most central collisions. Quoted errors are statistical only, the systematic errors are estimated to be about 10% for Ξ and about 15% for Ω.

Ξ^-	1.21±0.09
$\overline{\Xi}^+$	0.076±0.017
Ω^-	0.071±0.036
$\overline{\Omega}^+$	0.020±0.010

In order to be able to establish whether hyperon production is already enhanced at 40 A GeV/c and by how much, we need p-Be reference data at the same beam energy. A significant sample of p-Be data has been collected by NA57 (see Table 1) and the analysis is currently ongoing: its results will allow us to study how the enhancements depend on the beam energy.

In Figure 7, Ξ and Ω yields at 40 A GeV/c are compared with the corresponding values at 158 A GeV/c . For the comparison, hyperon results at 158 A GeV/c have been limited to the three most central classes (see Figure 5), corresponding to the same fraction of cross section as for 40 A GeV/c . While Ξ^- yield is similar at 40 and 158 GeV, $\overline{\Xi}^+$, Ω^- and $\overline{\Omega}^+$ are produced less abundantly at lower beam energy. This picture is compatible with an increase of the baryon density at lower beam momenta.

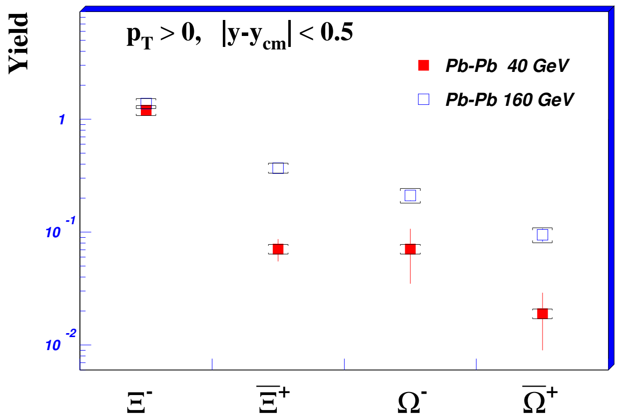

Figure 7. Ξ and Ω yields in the approximately 25% most central Pb-Pb collisions at 40 and 158 A GeV/c .

In Figure 8 the NA57 Ξ and Ω yields at both energies are compared with the preliminary results of STAR experiment at RHIC. STAR results are based on the 14% most central collisions [12][1]. For comparison, the NA57 particle yields at both energies have been computed for the two most central classes, i.e. class 3 + class 4, at 158 A GeV/c (see Figure 5), corresponding to about the 12% most central collisions. The Ξ^- and Ω^- yields show a much weaker energy dependence than their anti-particles. In particular, at RHIC energy the production rate for hyperon and anti-hyperon is about the same.

In Figure 9 the anti-hyperon/hyperon ratios are shown as a function of $\sqrt{s}$ from NA57 to STAR energies. The $\overline{\Lambda}/\Lambda$ ratio at 40 A GeV/c is also shown, although not corrected for acceptance and efficiency. However, the corrections to the anti-particle/particle ratios are small due to the left/right symmetry of the NA57 apparatus and the reversing of the magnetic field operated during the data taking. In order to have large enough statistics, the NA57 ratios are computed at both energies over about the 25% most central collisions, corresponding to the three most central classes (2 + 3 + 4), where all hyperon yields show a weak centrality dependence. All ratios increase with energy, approaching 1 at RHIC energy. The energy dependence is weaker for particle with higher strangeness content.

[1]The comparison presented in this paper is based on the preliminary results from STAR available before this Quark Matter Conference. The updated results on the hyperon yields presented at this Conference from STAR Collaboration confirm the energy dependence described in the following.

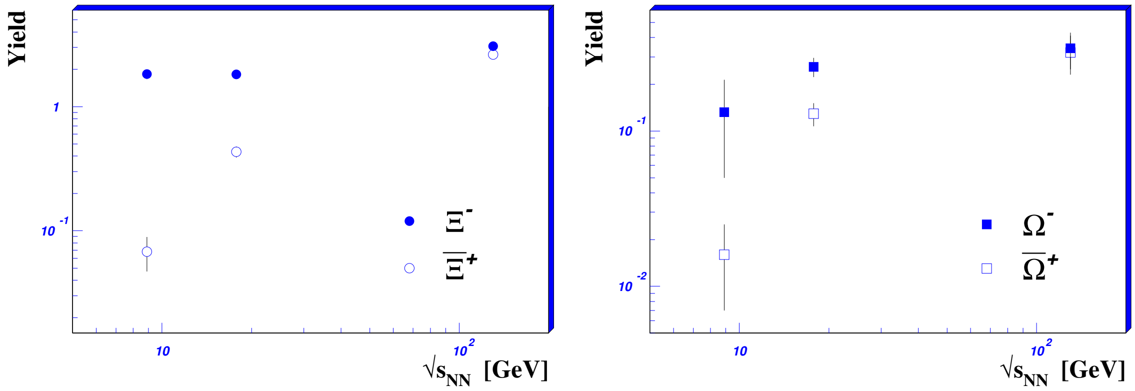

Figure 8. Comparison of Ξ and Ω yields from NA57 and STAR results.

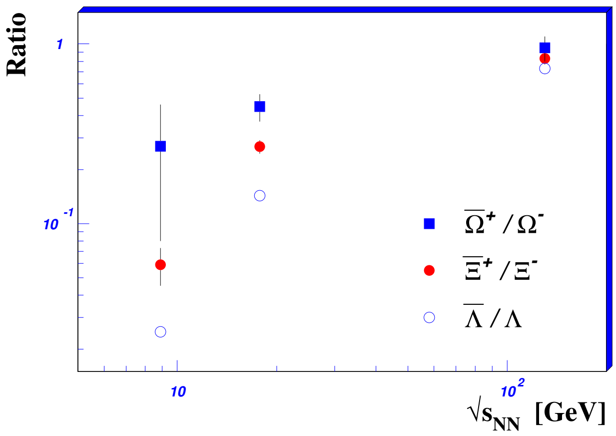

Figure 9. Comparison of anti-hyperon/hyperon ratios from NA57 and STAR results.

5. Conclusions and Outlook

The NA57 results on hyperon production in Pb-Pb at 158 A GeV/c confirm the pattern of enhancements relative to p-Be observed by WA97: the particle yields per wounded nucleon increase with the strangeness content of the particle, up to a factor 20 for $\Omega^{-}+\overline{\Omega}^{+}$. This result is considered as one of the most compelling pieces of evidence that colour deconfined matter is produced in central Pb-Pb collisions at SPS energies [2].

The first results on Ξ and Ω yields in Pb-Pb collisions at 40 A GeV/c indicates a larger baryon density with respect to 158 A GeV/c .

The anti-hyperon/hyperon ratios increase with energy, approaching 1 at RHIC. The energy dependence of the ratio is weaker for particle with higher strangeness content.

The ongoing analysis of the p-Be data sample at 40 GeV/c will allow us to measure the energy dependence of the strangeness enhancement.

A further investigation of the centrality dependence of the hyperon enhancements would be possible exposing the existing NA57 apparatus to the In beam from the SPS in year 2003. Since Pb-Pb collisions with $N_{wound} < 100$ are rather peripheral, it would be important to cross-check the observed effects in more central collisions with a lighter system; such a system may also allow to explore a region of smaller N_{wound}.

REFERENCES

1. S. Margetis, K. Šafařík and O. Villalobos Baillie, Annu. Rev. Nucl. Part. Sci. 50 (2000) 299
2. U. Heinz and M. Jacob, nucl-th/0002042 (2000) and references therein
   see also www.cern.ch/CERN/Announcements/2000/NewStateMatter
3. J. Rafelski and B. Müller, Phys. Rev. Lett. 48 (1982) 1066
   J. Rafelski and B. Müller, Phys. Rev. Lett. 56 (1986) 2334
   P. Koch, B. Müller and J. Rafelski, Phys. Rep. 142 (1986) 167
4. E. Andersen et al., Phys. Lett. B 449 (1999) 401
   F. Antinori et al., Nucl. Phys. A661 (1999) 130c
5. V. Manzari et al., J. Phys. G: Nucl. Part. Phys. 25 (1999) 473
   V. Manzari et al., Nucl. Phys. A661 (1999) 716c
6. C.Y. Wong, Introduction to High-Energy Heavy-Ion Collisions (World Scientific Publishing, Singapore 1994) 251 and references therein
7. N. Carrer et al., J. Phys. G: Nucl. Part. Phys. 27 (2001) 391
8. F. Antinori et al., Eur. Phys. J. C 14 (2000) 633
9. N. Carrer et al., Nucl. Phys. A 698 (2002)118c
10. K. Fanebust et al., J. Phys. G: Nucl. Part. Phys. 28 (2002) 1607
11. D. Elia et al., this Proceedings
12. J. Castillo et al., J. Phys. G: Nucl. Part. Phys. 28 (2002) 1987
    B. Hippolyte, PhD thesis, Université de Strasbourg