Production of Lambda and Antilambda hyperons was measured in central Pb-Pb collisions at 40, 80, and 158 A·GeV beam energy on a fixed target. Transverse mass spectra and rapidity distributions are given for all three energies. The \( \Lambda/\pi \) ratio exhibits a monotonic increase.

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Production of Lambda and Antilambda hyperons was measured in central Pb-Pb collisions at 40, 80, and 158 A·GeV beam energy on a fixed target. Transverse mass spectra and rapidity distributions are given for all three energies. The \( \Lambda/\pi \) ratio at mid-rapidity and in full phase space shows a pronounced maximum between the highest AGS and 40 A·GeV SPS energies, whereas the \( \overline{\Lambda}/\pi \) ratio exhibits a monotonic increase.

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It was suggested\textsuperscript{11} that the onset of deconfinement should cause a non-monotonic energy dependence of the total strangeness to pion ratio. This effect was recently observed in NA49 data on the energy dependence of kaon and pion production in central Pb-Pb collisions\textsuperscript{12,13} where a sharp maximum of the $K^+ / \pi^+$ ratio is seen at 30 A·GeV beam energy. To obtain an estimate of the energy dependence of total strangeness production and to study how the strange quarks and anti-strange quarks are distributed among the relevant hadronic species, it is important to complement the data of Refs.\textsuperscript{14,15} on $K^+ \text{ and } K^-$ yields by data on both $\Lambda$ and $\bar{\Lambda}$ production.

In this letter we present measurements of $\Lambda$ and $\bar{\Lambda}$ production in central Pb-Pb collisions at 40, 80, and 158 GeV per nucleon over a wide range in rapidity ($|y| \leq 1.6$, where $y$ is the rapidity in the cms) and transverse mass $m_T (0 \leq (m_T - m_0) \leq 1.6 \text{ GeV}/c^2$, where $m_0$ is the $\Lambda$ mass). Preliminary analyses have been reported in Refs.\textsuperscript{12,13}.

The NA49 detector is a large acceptance hadron spectrometer\textsuperscript{16}. Tracking and particle identification by measuring the specific energy loss $dE / dx$ is performed by two Time Projection Chambers (Vertex-TPCs), located inside two vertex magnets, and two large volume TPCs (Main-TPCs) situated downstream of the magnets symmetrically to the beam line. The relative $dE / dx$ resolution is 4% and the momentum resolution $\sigma(p)/p^2 = 0.3 \times 10^{-4}$ (GeV/c)$^{-1}$. Centrality selection is based on a measurement of the energy deposited in a forward calorimeter by the projectile spectator nucleons. For the present analysis, the 7.2% most central interactions at 40 and 80 A·GeV were selected. Using the Glauber model to convert a cross section fraction into the number of wounded nucleons $\langle N_W \rangle$ per event this corresponds, on average, to $\langle N_W \rangle = 349$\textsuperscript{12}. For 158 A·GeV the 10% most central events were selected ($\langle N_W \rangle = 335$). About 400 000 events were analyzed for 40 and 158 A·GeV each and 300 000 events for 80 A·GeV.

$\Lambda$ and $\bar{\Lambda}$ hyperons are identified by reconstructing their decay topologies $\Lambda \rightarrow p + \pi^-$ and $\bar{\Lambda} \rightarrow \bar{p} + \pi^+$, respectively (branching ratio 63.9%). Candidates were found by forming pairs from all measured positively and negatively charged particles requiring a distance of closest approach between the two trajectories of less than 1 cm at any point before reaching the target plane. To reduce the combinatorial background from random pairs a set of quality cuts\textsuperscript{17} was imposed on the position of the secondary vertex (at least 30 cm downstream from the target and outside the sensitive volume of the TPCs), on the impact parameter of the parent and the daughter tracks in the target plane, and on the number of points measured in the TPC. At 158 A·GeV an additional geometric quality cut was applied, which excludes particles in the high transverse mass region from the analysis\textsuperscript{17}. This results in a decreased acceptance for $\Lambda$ and $\bar{\Lambda}$ at low transverse mass. For each $\Lambda$ ($\bar{\Lambda}$) candidate the invariant mass was calculated assuming that the positive track is a proton ($\pi^+$) and the negative track is a $\pi^-$ ($\bar{p}$). To enrich the decay protons (anti-protons) a cut on the specific energy loss $dE / dx$ of the positive (negative) tracks of $\pm 4 \sigma$ from the expected mean value was applied. In Fig.\textsuperscript{1} the resulting invariant mass distributions of ($p\pi^-$) and ($\bar{p}\pi^+$) pairs at 158 A·GeV are shown. Clear signals are observed. The peak positions are in agreement with the nominal value of the Lambda hyperon mass\textsuperscript{18}. The mass resolution ($\sigma_m$) is about 2 MeV/c$^2$ at all three energies. The background was subtracted using a third-order polynomial. Corrections for geometrical acceptance, branching ratio and tracking efficiency were calculated bin by bin in rapidity and transverse momentum using GEANT 3.21 for detector simulation and dedicated NA49 simulation software\textsuperscript{17}. The systematic errors were estimated by varying the quality cuts and by analyzing selected subvolumes of the TPCs and were found to be smaller than 9%. Corrections for feed-down from weak decays (mostly $\Xi^-$, $\Xi^0$ and their anti-particles) are not applied and were estimated to be about $(6 \pm 3)\%$ for $\Lambda$ and $(12 \pm 6)\%$ for $\bar{\Lambda}$. A detailed study shows a weak $p_T$ and rapidity dependence. In the following $\Lambda$ ($\bar{\Lambda}$) include those from electro-magnetic $\Sigma^0$ ($\Sigma^0$) decays. The transverse mass distributions at mid-rapidity ($|y| \leq 0.4$) are shown in Fig.\textsuperscript{2}. All spectra are fitted by an exponential function in $m_T$:

$$\frac{1}{m_T} \frac{d^2n}{dm_Tdy} \propto \exp \left( -\frac{m_T}{T} \right),$$

where $T$ is the inverse slope parameter. The fitted range (in $m_T - m_0$) is 0.4–1.4 GeV/c$^2$. The results are summarized in Tab.\textsuperscript{1}. In this fit region, the $\Lambda$ inverse slope parameter $T$ increases with collision energy. The deviations at low transverse mass, seen in Fig.\textsuperscript{2} for 40 and 80 A·GeV, and the convex shape of the spectra, indicate the effect of transverse flow\textsuperscript{19}.
are obtained by integrating the measured $p_T$ spectra and by extrapolation into unmeasured regions. At 40 and 80 A·GeV the acceptance covers the full transverse momentum range down to $p_T = 0$. At 158 A·GeV the $p_T$ integration was started at $p_T = 0.6$ GeV/c. The extrapolation to the full $p_T$ range was performed by multiplying with factors 1.41 ($\Lambda$) and 1.35 ($\bar{\Lambda}$), which were derived from the 80 A·GeV $p_T$ spectra. Using the fitted exponential functions or a combined fit of a blast-wave model to the NA49 particle spectra at 158 A·GeV [13] would result in 5-10% different extrapolation factors. This uncertainty is included in the estimated systematic errors. The resulting rapidity distributions of $\Lambda$ and $\bar{\Lambda}$ hyperons are compared in Fig. 3. The $\Lambda$ rapidity distribution at 40 A·GeV is peaked at mid-rapidity whereas this distribution becomes broader and flatter with increasing energy. Since $\Lambda$ hyperons carry a significant fraction of the total net baryon number their rapidity distribution reflects the overall net baryon number distribution which is not peaked at mid-rapidity due to incomplete stopping of the incoming nucleons at top SPS energy. The same behaviour was observed for the $\bar{\Lambda}$ distribution at mid-rapidity (|$y$| ≤ 0.4). The full lines are exponential fits described in the text.

![FIG. 2: Transverse mass spectra of $\Lambda$ and $\bar{\Lambda}$ at mid-rapidity (|$y$| ≤ 0.4). The full lines are exponential fits described in the text.](image)

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![FIG. 3: Rapidity distribution of $\Lambda$ (top) and $\bar{\Lambda}$ (bottom) at 40, 80, and 158 A·GeV beam energy (full symbols). The open symbols show the measured points, reflected with respect to $y = 0$. The errors are statistical only. The full lines represent fits to the data which were used to obtain total yields.](image)
measurement at $\sqrt{s_{NN}} = 130$ GeV [28] follows this trend. The $\langle \Lambda \rangle/\langle \pi \rangle$ ratio, however, shows a monotonic increase up to RHIC energies [28] without significant structure. Qualitatively, the maximum in the $\langle \Lambda \rangle/\langle \pi \rangle$ ratio can be understood to arise from the interplay of the opening of the threshold of $\Lambda$-K associate production and the rapidly decreasing net baryon density in the produced fireball. In contrast, $\Xi$ production is not sensitive to the net baryon density and shows a continuous threshold increase. For elementary p-p interactions [29, 30], the $\langle \Lambda \rangle/\langle \pi \rangle$ ratio shows an increase up to $\sqrt{s_{NN}} = 5$ GeV followed by a saturation at higher energies (cf. Fig. 4) with a similar trend observed in the $\langle \Lambda \rangle/\langle \pi \rangle$ ratio (cf. Fig. 5). It is seen that both ratios are, at all energies, significantly below the A-A results. Consequently, $\Lambda$ and $\Xi$ production in A-A collisions cannot be understood as a superposition of nucleon-nucleon interactions. The observed strangeness enhancement is expected from the statistical hadronization model [10, 31, 32] which explains it as the fading-away of canonical strangeness suppression, characterizing the comparatively small fireball volume in p-p collisions.

Turning to the $\sqrt{s}$-dependence of strange to non-strange yield ratios we note, first, a close correspondence between the present $\Lambda$, $\Xi$ hyperon data and the $K^+$, $K^-$ data previously obtained by NA49 [12] for central Pb-Pb collisions at 40, 80, and 158 A-GeV. Both the $\langle \Lambda \rangle/\langle \pi \rangle$ and $\langle K^+ \rangle/\langle \pi \rangle$ ratios exhibit a distinct peak occurring between a steep rise toward top AGS energies, and a smooth fall-off from 40 A-GeV onward to RHIC energy. On the contrary both $\langle \Xi \rangle/\langle \pi \rangle$ and $\langle K^- \rangle/\langle \pi \rangle$ ascend monotonically toward RHIC energy. The latter yields are not affected by the steep fall of the baryo-chemical potential. Since $\langle \Lambda \rangle \gg \langle \Xi \rangle$ and $\langle K^+ \rangle \gg \langle K^- \rangle$ in the interval from top AGS to low SPS energies, the $\Lambda$ hyperons and $K^+$ carry a major fraction of the overall $s$ and $\pi$ quark production. Thus $s + \bar{\pi}$ production, relative to $u + \bar{u} + d + \bar{d}$ production (as captured mostly in the pion yield) must reach a maximum within the interval $\sqrt{s} \approx 5$ GeV (top AGS energy) and $\sqrt{s} = 8.7$ GeV (the lowest SPS energy covered in the present study). As the corresponding p-p ratios vary much less over this energy range we finally conclude that the relative "strangeness enhancement" in A-A collisions reaches a maximum within this range.

The observed $\sqrt{s}$-dependence is confronted in Figs. 4 and 5 with predictions from the statistical hadronization model [32] and from the microscopic transport models UrQMD [33, 34] and HSD [33, 35]. The former employs a $(T, \mu_B)$ relation derived from a wide body of hadron production data [32]. The hadron gas model closely reproduces the $\langle \Lambda \rangle/\langle \pi \rangle$ ratio, but it underpredicts the $\langle \Xi \rangle/\langle \pi \rangle$ measurements. The transport models also predict the main trend of the energy dependence of the ratios. However, they do not provide a quantitative description.

In summary, we have presented evidence for a relative strangeness enhancement maximum within the interval $5 \leq \sqrt{s} \leq 8$ GeV, as inferred both from the present hyperon data and from our previous kaon data [12]. Upcoming analysis of data gathered at the SPS inside this interval will decide as to whether the relatively smooth maximum implied by the $(T, \mu_B)$ relation assumed in the statistical hadronization model [32] captures the detailed features of that strangeness peak. First such $K^+/\pi^+$ results obtained at $\sqrt{s} = 7$ GeV [13] seem to rather indicate a sharp peak as was predicted for the onset of deconfinement, e.g. in Ref. [11].

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[1] J. Bartke et al., Z. Phys. C48, 191 (1990).
[2] T. Alber et al., Z. Phys. C64, 195 (1994).
[3] C. Adler et al., nucl-ex/0206008.
[4] K. Adcox et al., Phys. Rev. Lett. 88, 242301 (2002).
[5] L. Ahle et al., Phys. Rev. C60, 044904 (1999).
[6] J. Cleymans, H. Oeschler, and K. Redlich, Phys. Lett. B485, 27 (2000).
[7] R. Hagedorn, Nucl. Phys. B24, 93 (1970).
[8] J. Rafelski and B. Müller, Phys. Rev. Lett. 48, 1066 (1982).
[9] F. Karsch, Nucl. Phys. A698, 199c (2002).
[10] A. Tounsi and K. Redlich, J. Phys. G28, 2095 (2002).
[11] M. Gaźdicki and M.I. Gorenstein, Acta Phys. Polon. B30, 2705 (1999).
[12] S.V. Afanasiev et al., Phys. Rev. C66, 054902 (2002).
[13] V. Friese et al., J. Phys. G30, 119 (2004).
[14] A. Mischke et al., J. Phys. G28, 1761 (2002).
[15] A. Mischke et al., Nucl. Phys. A715, 453c (2003).
[16] S.V. Afanasiev et al., Nucl. Instrum. Meth. A430, 210 (1999).
[17] A. Mischke, Ph.D. thesis, University of Frankfurt (2002).
[18] K. Hagiwara et al. (Particle Data Group), Phys. Rev. D66, 010001 (2002).
[19] E. Schnedermann, J. Sollfrank, and U. Heinz, Phys. Rev. C48, 2462 (1993).
[20] H. Appelshäuser et al., Phys. Rev. Lett. 82, 2471 (1999).
[21] F. Antinori et al., Eur. Phys. J. C14, 633 (2000).
[22] W. Schnitz et al., J. Phys. G28, 1861 (2002).
[23] J.L. Klay et al., Phys. Rev. C68, 054905 (2003).
[24] L. Ahle et al., Phys. Rev. C57, 466 (1998).
[25] C. Pinkenburg et al., Nucl. Phys. A698, 495c (2002).
[26] S. Albergo et al., Phys. Rev. Lett. 88, 062301 (2002).
[27] F. Becattini et al., Phys. Rev. C64, 024901 (2001), the total lambda yield is obtained from the E891 mid-rapidity measurement.
[28] C. Adler et al., Phys. Rev. Lett. 89, 092301 (2002).
[29] M. Gaźdicki and D. Röhrich, Z. Phys. C71, 55 (1996).
[30] M. Gaźdicki and D. Röhrich, Z. Phys. C65, 215 (1995).
[31] A. Tounsi, A. Mischke, and K. Redlich, Nucl. Phys. A715, 565c (2003).
[32] P. Braun-Munzinger, J. Cleymans, H. Oeschler, and K. Redlich, Nucl. Phys. A697, 902 (2002), and private communication.
[33] H. Weber, E.L. Bratkovskaya, W. Cassing, and H. Stöcker, Phys. Rev. C67, 014904 (2003).
[34] H. Weber, E.L. Bratkovskaya, and H. Stöcker, Phys. Rev. C66, 054903 (2002), and private communication.
[35] W. Cassing, Nucl. Phys. A700, 618 (2002).
[36] B.B. Back et al., Phys. Rev. Lett. 87, 242301 (2001).