K_S^0 and Λ Production in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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The ALICE measurement of K_S^0 and Λ production at midrapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is presented. The transverse momentum (p_T) spectra are shown for several collision centrality intervals and in the p_T range from 0.4 GeV/c (0.6 GeV/c for Λ) to 12 GeV/c. The p_T dependence of the Λ/K_S^0 ratios exhibits maxima in the vicinity of 3 GeV/c, and the positions of the maxima shift towards higher p_T with increasing collision centrality. The magnitude of these maxima increases by almost a factor of three between most peripheral and most central Pb-Pb collisions. This baryon excess at intermediate p_T is not observed in pp interactions at $\sqrt{s} = 0.9$ TeV and at $\sqrt{s} = 7$ TeV. Qualitatively, the baryon enhancement in heavy-ion collisions is expected from radial flow. However, the measured p_T spectra above 2 GeV/c progressively decouple from hydrodynamical-model calculations. For higher values of p_T, models that incorporate the influence of the medium on the fragmentation and hadronization processes describe qualitatively the p_T dependence of the Λ/K_S^0 ratio.

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Collisions of heavy nuclei at ultrarelativistic energies are used to investigate a deconfined high temperature and density state of nuclear matter, the quark-gluon plasma. It was observed at the Relativistic Heavy Ion Collider (RHIC) [1,2], that the Λ/K_S^0 and p/π ratios at intermediate p_T (2–6 GeV/c) are markedly enhanced in central heavy-ion collisions when compared with peripheral or pp results. A similar observation was also made at the Super Proton Synchrotron [3]. These observations led to a revival and further development of models based on the premise that deconfinement opens an additional mechanism for hadronization by allowing two or three soft quarks from the bulk to combine forming a meson or a baryon [4,5]. If the (anti-)quarks generated by (mini)jet fragmentation are also involved in recombination [6], the baryon enhancement could even extend up to 10–20 GeV/c [7].

The relative contribution of different hadronization mechanisms changes with hadron momentum. While at intermediate p_T recombination might be dominating, hydrodynamical radial flow contributes to the baryon enhancement at lower p_T, and fragmentation could take over at higher p_T. For this reason, it is important to identify baryons and mesons in a wide momentum range, which can be achieved by the topological decay reconstruction of K_S^0 and Λ particles.

In this Letter we present the K_S^0 and Λ p_T spectra and the Λ/K_S^0 ratios from Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV recorded by the ALICE Collaboration [8] in November 2010. The p_T dependence of the Λ/K_S^0 ratios is compared with pp results obtained at $\sqrt{s} = 0.9$ and 7 TeV, that bracket the Pb-Pb measurements in energy.

For the analysis presented here, we used the time projection chamber (TPC) and the inner tracking system to reconstruct charged particle tracks within the pseudorapidity interval of $|\eta| < 0.9$. For the offline analysis, we accepted only events with the primary vertex position within ± 10 cm of the detector center and with at least one particle hit in each of the trigger detectors (Silicon Pixel Detector, VZERO-A and VZERO-C). The events were classified by the collision centrality, based on the amplitude distribution in the VZERO counters fitted with a Glauber model description as discussed in Ref. [9]. The final data sample contained 1.6×10^7 events in the 0%–90% centrality range, corresponding to an integrated luminosity of 2.3 ± 0.1 μb^{-1}.

The weakly decaying K_S^0 and Λ were reconstructed using their distinctive V-shaped decay topology in the channels (and branching ratios) $K_S^0 \to \pi^+\pi^-$ (69.2%) and $\Lambda \to p\pi^-$ (63.9%) [10]. The reconstruction method forms so-called V0 decay candidates and the details are described in Ref. [11]. Because of the large combinatorial background in Pb-Pb collisions, a number of topological selections had to be more restrictive than those used in the pp analysis [11]. In addition, we retained only the V0 candidates reconstructed in a rapidity window of $|y| < 0.5$, with their decay-product tracks within the acceptance window $|\eta| < 0.8$. To further suppress the background, we kept only V0 candidates satisfying the cut on the proper decay length $l_T m/p_T < 3c\tau (4c\tau)$, where l_T and m are the V0 transverse decay length and nominal Λ (K_S^0) mass [10], and $c\tau$ is 7.89 cm (2.68 cm) for Λ (K_S^0) [10]. For the Λ candidates with $p_T < 1.2$ GeV/c, a three-standard-deviation particle-identification cut on the difference

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between the specific energy loss (dE/dx) measured in the TPC and that defined by a momentum-dependent parametrization of the Bethe-Bloch curve was applied for the proton decay-product tracks. To reduce the contamination of Λ reconstructed as K^0_S, an additional selection was applied in the Armenteros-Podolanski variables [12] of K^0_S candidates, rejecting candidates with $p_T^{\rm arm} < 0.2 \times |\alpha^{\rm arm}|$. Here, $p_T^{\rm arm}$ is the projection of the positively (or negatively) charged decay-product momentum on the plane perpendicular to the V0 momentum. The decay asymmetry parameter $\alpha^{\rm arm}$ is defined as $\alpha^{\rm arm} = (p_\parallel^+ - p_\parallel^-)/(p_\parallel^+ + p_\parallel^-)$, where $p_\parallel^+(p_\parallel^-)$ is the projection of the positively (negatively) charged decay-product momentum on the momentum of the V0. The minimal radius of the fiducial volume of the secondary vertex reconstruction was chosen to be 5 cm to minimize systematic effects introduced by efficiency corrections. It was verified that the decay-length distributions reconstructed within this volume were exponential and agreed with the $c\tau$ values given in the literature [10].

The raw yield in each p_T bin was extracted from the invariant-mass distribution obtained for this momentum bin. The raw yield was calculated by subtracting a fit to the background from the total number of V0 candidates in the peak region. This region was $\pm 5\sigma$ for K^0_S, and $\pm(3.5\sigma + 2\ \mathrm{MeV}/c^2)$ (to better account for tails in the mass distribution at low p_T) for Λ. The σ was obtained by a Gaussian fit to the mass peaks. The background was determined by fitting polynomials of first or second order to sideband regions left and right of the peak region.

The overall reconstruction efficiency was extracted from a procedure based on HIJING events [13] and the GEANT3 [14] transport Monte Carlo simulation package, followed by detector simulations and reconstruction done with the ALICE software framework [15]. The efficiency included the geometrical acceptance of the detectors, track reconstruction efficiency, the efficiency of the applied topological selection cuts, and the branching ratios for the V0 decays. The typical efficiencies for both particles were about 30% for $p_T > 4\ \mathrm{GeV}/c$, dropping to 0 at $p_T \sim 0.3\ \mathrm{GeV}/c$. The efficiencies did not change with the event centrality for p_T above a few GeV/c. However, at lower $p_{\rm T}$, they were found to be dependent on the event centrality. For Λ at $p_T < 0.9\ \mathrm{GeV}/c$ the difference was about a factor 2 between the 0%–5% and 80%–90% centrality intervals. The final momentum spectra were corrected in each centrality bin separately.

The spectra of Λ were in addition corrected for the feed-down contribution coming from the weak decays of Ξ^- and Ξ^0. A two-dimensional response matrix, correlating the p_T of the detected decay Λ with the p_T of the decayed Ξ, was generated from Monte-Carlo simulations. By normalizing this matrix to the measured Ξ^- spectra [16], the distributions of the feed-down Λ were determined and subtracted from the inclusive Λ spectra. The phase space distributions and total yields for the Ξ^0 were assumed to be the same as for the Ξ^-. The feed-down correction was found to be a smooth function of p_T with a maximum of about 23% at $p_T \sim 1\ \mathrm{GeV}/c$ and monotonically decreasing to 0% at $p_T > 12\ \mathrm{GeV}/c$. As a function of centrality, this correction changed by only a few percent.

Since the ratio Ω^-/Ξ^- in Pb-Pb collisions of different centralities at $\sqrt{s_{NN}} = 2.76$ TeV does not exceed 0.18 [16], and taking into account that the branching ratio $\Omega^- \to \Lambda K^-$ is 67.8% [10], the feed-down contribution from decays of Ω^- baryons is less than 1.5%, which is negligible compared with other sources of uncertainty (see below). We did not correct the Λ spectra for the feed-down from non-weak decays of Σ^0 and the $\Sigma(1385)$ family.

The fraction of Λ's produced in hadronic interactions with the detector material was estimated using the Monte Carlo simulations mentioned above, found to be less than 1%, and was neglected.

The following main sources of systematic uncertainty were considered: raw yield extraction, feed-down, efficiency corrections, and the uncertainty on the amount of crossed material. These were added in quadrature to yield the overall systematic uncertainty on the p_T spectra for all centralities.

The systematic uncertainties on the raw yields were estimated by using different functional shapes for the background and by varying the fitting range. Over the considered momentum range, the obtained raw yields varied within 3% for K^0_S and 4%–7% for Λ.

As a measure for the systematic uncertainty of the feed-down correction, we used the spread of the values determined for different centrality ranges with respect to the feed-down correction estimated for minimum bias events. This deviation was found to be about 5% relative to the overall Λ yield.

The systematic uncertainty associated with the efficiency correction was evaluated by varying one-by-one the topological, track selection, and particle-identification cuts. The cut variations were chosen such that the extracted uncorrected yield of the K^0_S and Λ would change by 10%. To measure the systematic uncertainty related to each cut, we used as a reference the corrected spectrum obtained with the nominal cut values. For Λ, the feed-down correction was reevaluated and taken into account for every variation of the cut on the cosine of the pointing angle. The overall p_T-dependent systematic uncertainty associated with the efficiency correction was then estimated by choosing the maximal (over all cut variations) deviation between varied and nominal spectra values obtained in each momentum bin. For the momentum range considered, this systematic uncertainty was determined to be 4%–6% for both K^0_S and Λ.

The systematic uncertainty introduced because of possible imperfections in the description of detector material in the simulations was estimated in Ref. [11] and amounted to 1.1%–1.4% for K^0_S and 1.6%–3.4% for Λ.

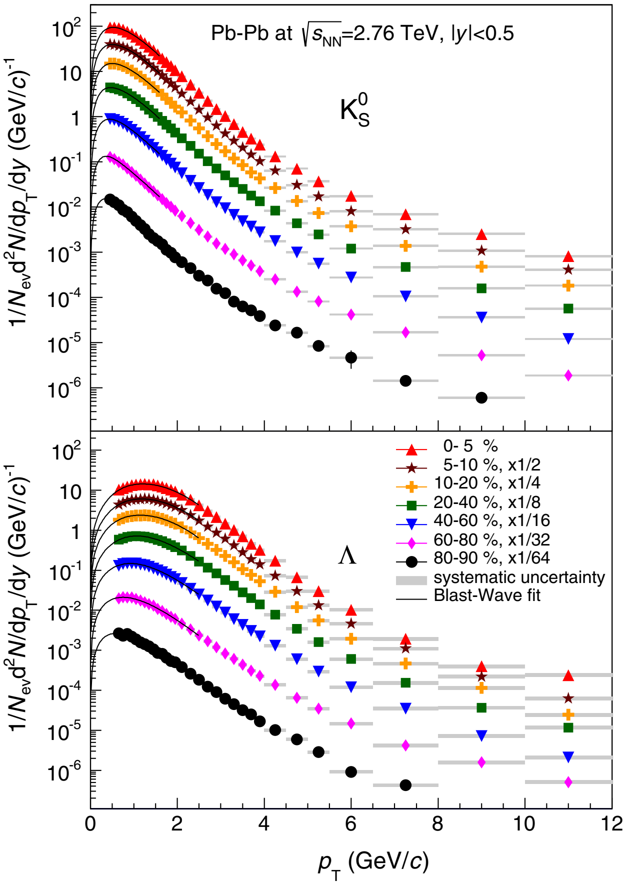

FIG. 1 (color online). K^0_S and Λ p_T spectra for different event centrality intervals. The curves represent results of blast-wave fits [17].

Since the systematic uncertainties related to the efficiency correction are correlated for the Λ and K^0_S spectra, they partially cancel in the Λ/K^0_S ratios. These uncertainties were evaluated by dividing Λ and K^0_S spectra obtained with the same cut variations and found to be half the size of those that would be obtained if the uncertainties of the Λ and K^0_S spectra were assumed to be uncorrelated. Altogether, over the considered momentum range, the maximal systematic uncertainty for the measured Λ/K^0_S ratios was found to be about 10%.

The corrected p_T spectra, fitted using the blast-wave parameterization described in Ref. [17], are shown in Fig. 1. The fit range in p_T was from the lowest measured point up to 2.5 GeV/c (1.6 GeV/c) for Λ (K^0_S). The fitting functions were used to extrapolate the spectra to zero p_T to extract integrated yields dN/dy. The results are given in Table I. The systematic uncertainties of the integrated yields were determined by shifting the data points of the spectra simultaneously within their individual systematic uncertainties and reapplying the fitting and integration procedure. In addition, an extrapolation uncertainty was estimated, by using alternative (polynomial, exponential, and Lévy-Tsallis [18,19]) functions fitted to the low-momentum part of the spectrum, and the corresponding difference in obtained values was added in quadrature.

The p_T dependence of the Λ/K^0_S ratios is presented in Fig. 2 (left). The Λ/K^0_S ratios observed in pp events at $\sqrt{s} = 0.9$ [11] and 7 TeV [20] agree within uncertainties over the presented p_T range, and they bound in energy the Pb-Pb results reported here. The ratio measured in the most peripheral Pb-Pb collisions is compatible with the pp measurement, where there is a maximum of about 0.55 at $p_T \sim 2$ GeV/c. As the centrality of the Pb-Pb collisions increases, the maximum value of the ratio also increases and its position shifts towards higher momenta. The ratio peaks at a value of about 1.6 at $p_T \sim 3.2$ GeV/c for the most central Pb-Pb collisions. This observation may be contrasted to the ratio of the integrated Λ and K^0_S yields which does not change with centrality (Table I). At momenta above $p_T \sim 7$ GeV/c, the Λ/K^0_S ratio is independent of collision centrality and p_T, within the uncertainties, and compatible with that measured in pp events.

A comparison with similar measurements performed by the STAR Collaboration in Au-Au collisions at $\sqrt{s_{NN}} =$ 200 GeV is shown in Fig. 2 (right). Since the antibaryon-to-baryon ratio at the LHC is consistent with unity for all p_T [21,22], the Λ/K^0_S and $\bar{\Lambda}/K^0_S$ ratios are identical and we show only the former. The STAR Λ/K^0_S and $\bar{\Lambda}/K^0_S$ ratios shown are constructed by dividing the corresponding p_T spectra taken from Ref. [23]. The quoted 15% p_T-independent feed-down contribution was subtracted from the Λ and $\bar{\Lambda}$ spectra. The shape of the distributions

TABLE I. Integrated yields, dN/dy, for Λ and K^0_S with uncertainties which are dominantly systematic. A blast-wave fit is used to extrapolate to zero p_T. Fractions of extrapolated yield are specified. Ratios of integrated yields, Λ/K^0_S, for each centrality bin with the total uncertainty, mainly from systematic sources, are shown.

		0%–5%	5%–10%	10%–20%	20%–40%	40%–60%	60%–80%	80%–90%
Λ	dN/dy	26 ± 3	22 ± 2	17 ± 2	10 ± 1	3.8 ± 0.4	1.0 ± 0.1	0.21 ± 0.03
	$p_T < 0.6$ GeV/c frac.	10%	11%	12%	14%	18%	24%	32%
K^0_S	dN/dy	110 ± 10	90 ± 6	68 ± 5	39 ± 3	14 ± 1	3.9 ± 0.2	0.85 ± 0.09
	$p_T < 0.4$ GeV/c frac.	20%	21%	21%	23%	25%	31%	33%
	Ratio dN/dy Λ/K^0_S	0.24 ± 0.02	0.24 ± 0.02	0.25 ± 0.02	0.25 ± 0.02	0.26 ± 0.03	0.25 ± 0.02	0.25 ± 0.02

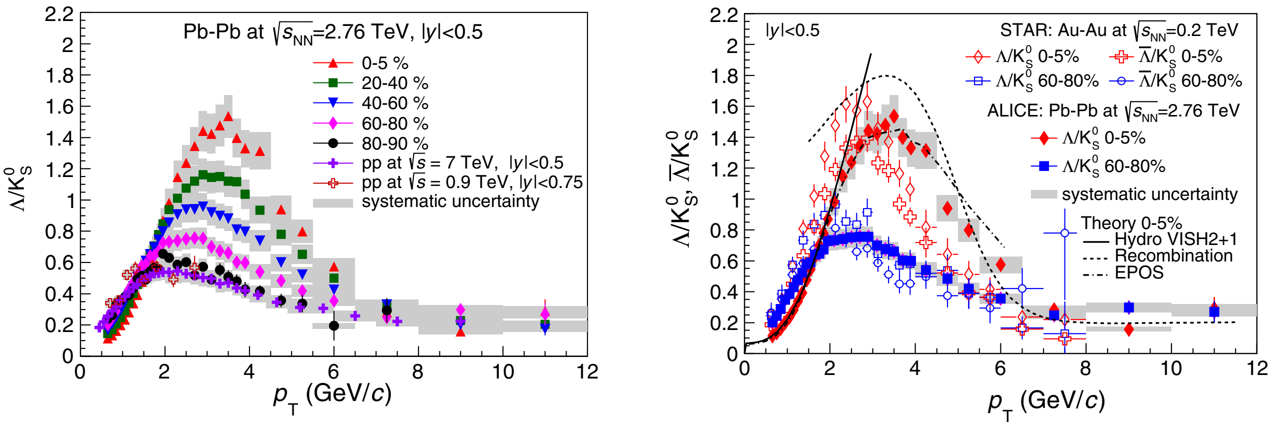

FIG. 2 (color online). Left: Λ/K^0_S ratios as a function of p_T for different event centrality intervals in Pb-Pb collisions at $\sqrt{s_{NN}} =$ 2.76 TeV and pp collisions at $\sqrt{s} = 0.9$ [11] and 7 TeV [20]. Right: selected Λ/K^0_S ratios as a function of p_T compared with Λ/K^0_S and $\bar{\Lambda}/K^0_S$ ratios measured in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [23]. The solid, dashed, and dot-dashed lines show the corresponding ratios from a hydrodynamical model [24–26], a recombination model [28] and the EPOS model [29], respectively.

of Λ/K^0_S and $\bar{\Lambda}/K^0_S$ are the same but they are offset by about 20% and have peak values around 10% higher, and, respectively, lower, than the ALICE data. This comparison between LHC and RHIC data shows that the position of the maximum shifts towards higher p_T as the beam energy increases. It is also seen that the baryon enhancement in central nucleus-nucleus collisions at the LHC decreases less rapidly with p_T, and, at $p_T \sim 6$ GeV/c, it is a factor of 2 higher compared with that at RHIC.

Also shown in the right panel of Fig. 2 is a hydrodynamical model calculation [24–26] for most central collisions, which describes the Λ/K^0_S ratio up to p_T about 2 GeV/c rather well, but for higher p_T progressively deviates from the data. Such decoupling between the calculations and measurements is already seen in the comparison with p_T spectra [27]. The agreement for other charged particles is improved when the hydrodynamical calculations are coupled to a final-state rescattering model [28]. Therefore, it would be interesting to compare these data and their centrality evolution with such treatment. For higher p_T, a recombination model calculation [5] is presented (Fig. 2, right). It approximately reproduces the shape, but overestimates the baryon enhancement by about 15%. We also show a comparison of the EPOS model calculations [29] with the current data. This model takes into account the interaction between jets and the hydrodynamically expanding medium and arrives at a good description of the data.

In conclusion, we note that the excess of baryons at intermediate p_T, exhibiting such a strong centrality dependence in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, does not reveal itself in pp collisions at the center-of-mass energy up to $\sqrt{s} = 7$ TeV. For $p_T > 7$ GeV/c, the measured Λ/K^0_S ratios become constant within our uncertainties for all centralities and equal to that of the previously reported pp data. This agreement between collision systems suggests that the ratio of fragmentation into Λ and K^0_S at high p_T, even in central collisions, is not modified by the medium.

As the collision energy and centrality increase, the maximum of the $\Lambda(\bar{\Lambda})/K^0_S$ ratio shifts towards higher p_T, which is in qualitative agreement with the effect of increased radial flow, as predicted in Ref. [4]. The ratio of integrated Λ and K^0_S yields does not, within uncertainties, change with centrality and is equal to that measured in pp collisions at 0.9 and 7 TeV. This suggests that the baryon enhancement at intermediate p_T is predominantly due to a redistribution of baryons and mesons over the momentum range rather than due to an additional baryon production channel progressively opening up in more central heavy-ion collisions.

The width of the baryon enhancement peak increases with the beam energy. However, contrary to expectations [7], the effect at the LHC is still restricted to an intermediate-momentum range and is not observed at high p_T. This puts constraints on parameters of particle production models involving coalescence of quarks generated in hard parton interactions [30].

Qualitatively, the baryon enhancement presented here as p_T dependence of Λ/K^0_S ratios, is described in the low-p_T region (below 2 GeV/c) by collective hydrodynamical radial flow. In the high-p_T region (above 7–8 GeV/c), it is very similar to pp results, indicating that there it is dominated by hard processes and fragmentation. Our data provide evidence for the need to include the effect of the hydrodynamical expansion of the medium formed in Pb-Pb collisions in the mechanisms of hadronization.

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