Transverse mass distributions of strange particles produced in Pb-Pb collisions at 158 $A$ GeV/c

G. E. Bruno$^b$ for the NA57 Collaboration:

F Antinori$^i$, P Bacon$^a$, A Badalà$^f$, R Barbera$^a$, A Belogianni$^a$, A Bhasin$^e$, I J Bloodworth$^b$, M Bombara$^a$, G E Bruno$^b$, S A Bull$^e$, R Calandriolo$^b$, M Campbell$^b$, W Carena$^b$, N Carrer$^b$, R F Clarke$^e$, A Daines$^e$, A P de Haas$^a$, P C de Rijke$^e$, D Di Bari$^b$, S Di Liberto$^b$, R Divia$^b$, D Elia$^a$, D Evans$^e$, K Fanebus$^a$, G A Feofilov$^a$, R A Fini$^b$, P Gannot$^b$, B Ghidini$^b$, G Grella$^b$, H Helstrup$^d$, A K Holme$^a$, A Jacholkowski$^b$, G T Jones$^e$, P Jovanovic$^e$, A Jusko$^i$, R Kamermans$^b$, J B Kinson$^c$, K Knudsson$^b$, A A Kolozhvari$^i$, V Kondratiev$^a$, I Králik$^i$, A Kravčáková$^i$, P Kuijer$^e$, V Lenti$^b$, R Lietava$^i$, G Lovhøiden$^b$, V Manzari$^b$, G Martinska$^d$, M A Mazzoni$^a$, F Meddi$^e$, A Michalon$^i$, M Morando$^i$, F Navach$^b$, P I Norman$^c$, A Palmeri$^g$, G S Pappalardo$^b$, B Pastirčák$^i$, J Pišút$^i$, N Pisutova$^e$, E Quercigh$^f$, R Riggi$^b$, D Röhrich$^c$, G Romano$^b$, K Šafařík$^b$, L Sándor$^i$, E Schillings$^a$, G Segato$^b$, M Senè$^m$, R Senè$^m$, W Snoeys$^h$, F Soramel$^i$, M Spyrópolou-Stassinaki$^a$, P Staroba$^a$, T A Toulina$^i$, R Turrisi$^i$, T S Tveter$^a$, J Urbán$^i$, F F Valiev$^q$, A van den Brink$^p$, P van de Ven$^i$, P Vande Vyvre$^b$, N van Eijndhoven$^i$, J van Hunen$^b$, A Vascotto$^b$, T Vlk$^i$, O Villalobos Baillie$^e$, L Vinogradov$^q$, T Virgili$^b$, M F Votruba$^b$, J Vrláková$^i$ and P Závada$^a$

$^a$ Physics Department, University of Athens, Athens, Greece
$^b$ Dipartimento IA di Fisica dell’Università e del Politecnico di Bari and INFN, Bari, Italy
$^c$ Fysisk Institutt, Universitetet i Bergen, Bergen, Norway
$^d$ Høgskolen i Bergen, Bergen, Norway
$^e$ University of Birmingham, Birmingham, UK
$^f$ Comenius University, Bratislava, Slovakia
$^g$ University of Catania and INFN, Catania, Italy
$^h$ CERN, European Laboratory for Particle Physics, Geneva, Switzerland
$^i$ Institute of Experimental Physics, Slovak Academy of Science, Košice, Slovakia
$^j$ P.J. Šafárik University, Košice, Slovakia
$^k$ Fysisk Institutt, Universitetet i Oslo, Oslo, Norway
$^l$ University of Padua and INFN, Padua, Italy
$^m$ Collège de France, Paris, France
$^n$ Institute of Physics, Prague, Czech Republic
$^o$ University “La Sapienza” and INFN, Rome, Italy
$^p$ Dipartimento di Scienze Fisiche “E.R. Caianiello” dell’Università and INFN, Salerno, Italy
$^q$ State University of St. Petersburg, St. Petersburg, Russia
$^r$ Institut de Recherches Subatomique, IN2P3/ULP, Strasbourg, France
$^s$ Utrecht University and NIKHEF, Utrecht, The Netherlands

Experiment NA57 has collected high statistics, high purity samples of $K^0_S$, $\Lambda$, $\Xi$ and $\Omega$ produced in Pb-Pb collisions at 158 $A$ GeV/c. In this paper we present a study of the transverse mass spectra of these particles for a sample of events corresponding to about the most central 55% of the inelastic Pb-Pb cross section. We analyse the transverse mass distributions in the framework of the blast-wave model for the full sample under consideration and, for the first time at the SPS, as a function of the event centrality.

1 Introduction

The NA57 experiment has been designed to study the production of strange baryons and antibaryons in heavy ion collisions. The experiment has extended the WA97 [1] measurements to a wider centrality range and to a lower beam momentum. NA57 results on hyperon yields [2] at 158 $A$ GeV/c confirm the enhancement pattern observed by the WA97 experiment, with an enhancement factor increasing with increasing strangeness.

In this paper we shall concentrate on the analysis of the transverse mass ($m_T = \sqrt{p_T^2 + m^2}$) spectra for the $\Lambda$, $\Xi^-$, $\Omega^-$ hyperons, their antihyperons and $K^0_S$ measured in Pb-Pb collisions at 158 $A$ GeV/c.

2 The NA57 experiment

The layout of the NA57 experiment has been described in detail elsewhere [3]. A telescope of compactly packed silicon pixel detectors is used as main tracking device. Additional pixel and double-sided silicon microstrip detectors
are used to improve the momentum resolution for high-momentum tracks. The telescope inclination angle with respect to the beam line and the distance from the target are set to accept particles produced in about half a unit of rapidity around central rapidity and medium transverse momentum.

An array of scintillation counters provides a fast signal to trigger on the centrality of the collisions. A more precise centrality measurement is provided by two stations of silicon strip detectors. All detectors are located in the 1.4 T field of the Goliath magnet. The triggered fraction of the total inelastic cross section is about 55%.

The K⁰ mesons, the Λ, Ξ⁻ and Ω⁻ hyperons and their antiparticles are identified by reconstructing their weak decays into final states containing only charged particles. Decays are required to take place in a fiducial volume located between a fixed distance from the target and the first plane of the telescope. The selection procedure allows for extraction of hyperon and K⁰ signals with negligible background [4].

Events have been divided into five centrality classes (0,1,2,3,4), class 0 being the most peripheral and class 4 the most central, according to the charge particle multiplicity measured in the pseudorapidity intervals 2 < η < 3 and 3 < η < 4. The centrality of the collision is expressed as number of wounded nucleons computed from the measured trigger cross sections using the Glauber model. The centrality determination is described in detail in ref. [5].

3 Data sets and analysis

The results presented in this paper are based on the analysis of a data sample consisting of 460 M events of Pb-Pb collisions collected in the years 1998 and 2000. For each particle species we define the fiducial acceptance window using a Monte Carlo simulation of the apparatus, in order to exclude the border regions.

All data are corrected for geometrical acceptance and for detector and reconstruction inefficiencies on a particle-by-particle basis, using a Monte Carlo technique where simulated particles are embedded into real events (the procedure has been described in detail in [5]). The correction method is CPU intensive; therefore, while all the reconstructed Ξ⁺s and Ω⁺s have been individually weighted, for the much more abundant Κ⁰, Λ and Σ⁻ samples we only weighted a small fraction of the total sample in order to reach a statistical accuracy better than the limits imposed by the systematic error.

4 Inverse slopes of the transverse mass spectra

The double-differential (γ, m_T) distributions for each particle have been parametrized using the expression

\[ \frac{d^2N}{dN_\gamma dm_Tdy} = f(\gamma) \exp\left(-\frac{m_T}{T_{app}}\right) \]

assuming the rapidity distribution to be flat (f(\gamma) = const) within our acceptance region. The inverse slope parameter T_app (“apparent temperature”) has been extracted by means of a maximum likelihood fit of Eq. (1) to the data. As discussed in detail in the next section, this apparent temperature can be interpreted as due to the thermal motion coupled with a collective transverse flow of the fireball components assumed to be in thermal equilibrium.

Transverse mass distributions 1/m_T dN/dm_T for strange particles measured in the centrality range accessible to the experiment are shown in figure 1. The shapes of all spectra are well described by single exponential functions. In the next section, we shall attempt a global fit with the blast-wave model.

The inverse slope parameters T_app of the transverse mass spectra are given in table I. They are in agreement within the errors with those measured over a smaller centrality range (about 40% of the Pb-Pb inelastic cross section) by the WA97 experiment [1].

![Figure 1](attachment:image.png)
Table 1. Inverse slopes parameter $T_{app}$ (MeV) of the strange particles in the full centrality range (0-4). The first error is statistical, the second one systematic.

| Strange particle | Inverse Slope (MeV) |
|------------------|----------------------|
| $K^0$            | $237 \pm 4 \pm 24$  |
| $\Lambda$        | $289 \pm 7 \pm 29$  |
| $\Sigma^+$       | $287 \pm 6 \pm 29$  |
| $\Xi^-$          | $297 \pm 5 \pm 30$  |
| $\Omega^-$       | $316 \pm 11 \pm 30$ |
| $\Omega^+$       | $264 \pm 19 \pm 27$ |
| $\Sigma^-$       | $284 \pm 28 \pm 27$ |

5 Blast-wave description of the spectra

We consider in this section the statistical hadronization model of ref. [8] to describe the strange particle spectra discussed above. The model assumes that particles decouple from a system in local thermal equilibrium with temperature $T$, which expands both longitudinally and in the transverse direction; the quantum statistical distributions are approximated by the Boltzmann distribution. The longitudinal expansion is boost-invariant, the transverse one is defined in terms of a transverse velocity field.

The blast-wave model predicts a double differential cross section for a given particle $j$ of the form:

$$\frac{d^2N_j}{dmdT} = \int_0^{R_G} A_j m_T K_1 \left( \frac{m_T \cosh \rho}{T} \right) I_0 \left( \frac{m_T \sinh \rho}{T} \right) r dr \tag{2}$$

where $\rho = \tanh^{-1} \beta_+(r)$, $K_1$ and $I_0$ are two modified Bessel functions and $R_G$ is the transverse geometric (gaussian) radius of the source.

In a preliminary study [9], we considered a simplified model where the transverse flow velocity was assumed to be constant all along its profile: $\beta_+(r) = < \beta_+$ >. A more detailed analysis using different transverse velocity profiles has now been performed. We have also studied the stability of the fits (the parameters $T$ and $< \beta_+$ > are strongly anti-correlated), as well as their sensitivity to individual particle spectra. A complete description of the transverse mass spectrum analysis at 160 A GeV/c will be presented in a forthcoming publication [10]. In this new study, the transverse velocity field $\beta_+(r)$ has been parametrized according to power laws:

$$\beta_+(r) = \beta_S \left[ \frac{r}{R_G} \right]^n \quad r \leq R_G \tag{3}$$

where the exponent $n$ was assumed to be $n = 0, 1/2, 1$ or 2. Assuming a uniform particle density, the average transverse velocity is calculated according to $< \beta_+ > = \frac{2}{1+n} \beta_S$

As shown in fig. 2, the simultaneous best fit of eq. (3) ($n = 1$ profile case) to the data points of all the measured strange particle spectra successfully describes the data with $\chi^2/ndf = 37.2/48$, yielding the following values for the two basic quantities $T$ and $< \beta_+ >$:

$$T = 144 \pm 7 \text{(stat)} \pm 14 \text{(syst)} \text{ MeV}$$

$$< \beta_+ > = 0.381 \pm 0.013 \text{(stat)} \pm 0.012 \text{(syst)}.$$  

The quadratic profile is disfavoured by the data, yielding the largest value of $\chi^2$. The other two profiles ($n = 0$, $n = 1/2$) yield similar values of the freeze-out temperatures and of the average transverse flow velocities, as the $n = 1$ case, with good values of $\chi^2/ndf$. For the study of the centrality dependence of the freeze-out parameters presented below, the linear profile has been used.

The particles have been divided into two groups — those which share quarks in common with the nucleons and those which do not — and the fit procedure has been repeated separately for the two groups. The results of such fits are summarized in table 2. They suggest similar freeze-out conditions for the two groups. Since the interaction cross-sections for the particles of the two groups are quite different, this finding would suggest a similar production mechanism and final state interactions of limited importance (e.g. a rapid thermal freeze-out). A similar conclusion concerning the evolution of the system was reached in the study of the HBT correlation functions of negative pions at high $p_T$ in the WA97 experiment [11].

1It is known that the particles of the two groups may exhibit different production features, e.g. in the rapidity spectra.
For each hyperon species, the range of collision centrality (about the most central 55% of produced in Pb-Pb collisions at 158 GeV) freezes-out when the temperature is of the order of 120 MeV with an average transverse flow velocity of about one half of the speed of light. Particles with and without valence quarks in common with the nucleon appear to have similar behaviour. With increasing collision centrality, the transverse flow velocity increases and the final temperature decreases.

### References

1. E. Andersen et al. [WA97 Collaboration], Phys. Lett. B 449 (1999) 401
2. L. Sándor et al. [NA57 Collaboration], Proceeding of the 7th International Conference on Strange Quarks in Matter, to be published in J. Phys. G: Nucl. Part. Phys. (2003)
3. V. Manzari et al. [NA57 Collaboration], J. Phys. G: Nucl. Part. Phys. 25 (1999) 473
4. V. Manzari et al. [NA57 Collaboration], Nucl. Phys. A 661 761c
5. N. Carrer et al. [NA57 Collaboration], J. Phys. G: Nucl. Part. Phys. 27 (2001) 391
6. K. Fanebust et al. [NA57 Collaboration], J. Phys. G: Nucl. Part. Phys. 28 (2002) 160
7. F. Antinori et al. [WA97 Collaboration], Eur. Phys. J. C 14 (2000) 633
8. E. Schnedermann, J. Sollfrank and U. Heinz, Phys. Rev. C 48 (1993) 2462
9. G. E. Bruno et al. [NA57 Collaboration], Proceeding of the XXXVIII Rencontres de Moriond (2003) Preprint nucl-ex/0305033
10. F. Antinori et al. [NA57 Collaboration], being submitted to J. Phys. G: Nucl. Part. Phys.
11. F. Antinori et al. [WA97 Collaboration], J. Part. Phys. G: Nucl. Part. Phys. 27 (2001) 2325.