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Production of ϕ-mesons in p + p, p + Pb and central Pb + Pb collisions at $E_{\text{beam}} = 158\ A$ GeV

NA49 Collaboration

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Abstract

Yields and phase space distributions of ϕ-mesons emitted from p + p (minimum bias trigger), p + Pb (at various centralities) and central Pb + Pb collisions are reported ($E_{\text{beam}} = 158$ A GeV). The decay $\phi \to K^+K^-$ was used for identification. The ϕ/π ratio is found to increase by a factor of 3.0 ± 0.7 from inelastic p + p to central Pb + Pb. Significant enhancement in this ratio is also observed in subclasses of p + p events (characterized by high charged-particle multiplicity) as well as in the forward hemisphere of central p + Pb collisions. In Pb + Pb no shift or significant broadening of the ϕ-peak is seen.

1. Introduction

Strange-particle production is one of the observables expected to deliver detailed information on the reaction dynamics of ultrarelativistic nucleus–nucleus collisions [1]. In experiments at the CERN SPS accelerator it was found that the ratio of the number of produced kaons to that of pions is higher by a factor of about two compared to that in proton–proton reactions at the same energy [2–5]. In the past, several possible reasons for this strangeness enhancement have been discussed. Secondary interactions between the many hadrons created — about 2400 in a central Pb + Pb collision at 158 A GeV beam energy — may lead to an increase of the strange-particle fraction above that in p + p reactions, although the rate for this process is estimated to be relatively small. Secondly, and more interestingly, if nucleus–nucleus reactions proceed through a deconfined stage — in the limiting case with formation of a quark–gluon plasma (QGP) — then strange-quark production should be abundant [1]. Clearly, even if the colliding nucleons did not dissolve into a partonic phase, they would on average undergo several collisions. The stronger excitation might in turn lead to a strangeness enhancement [6]. This suggests to study particle production rates also as a function of the inelasticity or impact parameter in p + p and p + nucleus reactions.

In this context, ϕ-mesons play a particular role due to the $s\bar{s}$ composition of these mesons. Their yield should depend more sensitively than that of kaons on a strangeness enhancement stemming from the early partonic phase. Significantly enhanced production was proposed [7] as a QGP signature in nucleus–nucleus collisions. As hadrons they are in total strangeness-neutral; the strangeness is "hidden" and therefore without influence on a hadro-chemical equilibrium.

The present paper reports yields of ϕ-mesons measured via their K^+K^- decay channel by the NA49 experiment at the CERN SPS. The systems studied are:
– proton + proton (with minimum-bias trigger and with multiplicity selection),
– proton + Pb (at various centralities),
– Pb + Pb (with triggering on central collisions),

each at 158 A GeV beam energy and with fixed target. The event selections represent an attempt to investigate the evolution of strangeness enhancement when going from more elementary to increasingly complex reactions.

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2. Experiment

NA49 is a fixed-target experiment at CERN using external proton and, in particular, heavy-ion beams from the SPS. It is based on a hadron spectrometer that covers a large fraction of the solid angle and of the relevant momentum range. Four time-projection chambers (TPCs) provide charged-particle tracking as well as particle identification by $\mathrm{d}E/\mathrm{d}x$ measurement. In a limited momentum range — which, however, is very important for mid-rapidity kaons — time-of-flight detectors (TOF) supplement the particle identification capabilities of the system. The apparatus is described in detail in [8]. In the following, we focus on the features that are important for the present work.

For the investigation of the Pb + Pb reaction a 158 A GeV lead beam was used (typically 10^5 particles per 4.8 s spill/19.2 s cycle time). Beam contaminations were negligible. The solid Pb target had a thickness of 224 mg/cm^2, equivalent to 1% interaction probability. The 4% most central interactions, corresponding to an impact parameter range $b < 3.5$ fm, were selected by applying an appropriate upper limit on the energy transmitted in beam direction and measured by the zero-degree calorimeter. 10 to 20 events/spill were recorded. 380 000 events are used for this study.

For the measurement with protons the beam line was set to select secondary protons of 158 GeV (produced by the 450 GeV SPS beam). Typical intensities were 5×10^4 to 10^5 protons per 2.4 s extraction within the 14.4 s SPS cycle. The protons were identified by Cerenkov counters. The contamination by pions and kaons was below 10^{-3}.

In the p + p case a 14 cm long liquid-hydrogen target (1.95% interaction probability) was inserted. Only interactions in the central 11 cm were accepted in order to minimize contributions from interactions in the mylar windows. By means of "empty-target runs" they were found to be of the level of 1% over the whole multiplicity range of interest. The losses introduced by this fiducial cut depend on the accuracy, with which the position of the interaction vertex can be determined by back-extrapolating the tracks from the first TPC, and which therefore varies with the charged-particle multiplicity of the event. They decrease from 16% at $n_{\mathrm{ch}} = 4$ to 5% at $n_{\mathrm{ch}} = 10$ (the mean value of the multiplicity in p + p is $n_{\mathrm{ch}} = 7.2$). In this context, it is of importance that the position of the individual beam particles was measured by multi-wire chambers in the beam line with sub-millimeter accuracy. The "minimum-bias" event trigger used (28.9 mb) corresponds to 91% of the known inelastic p + p cross section (31.7 mb). 30 events/spill were recorded. The number of analyzed events is 400 000.

An essential additional feature in the p + Pb case was a centrality detector [8] counting the number n_{CD} of particles emitted from the Pb target nucleus in backward direction (mostly protons). n_{CD} is a measure of the mean number of collisions ν of the projectile inside the target (approximately $\nu \propto \sqrt{n_{\mathrm{CD}}}$ [9]). 180 000 events were analyzed.

The NA49 spectrometer accepts about 80% of all emitted particles. The requirements of kaon identification restricted the analysis of the ϕ-yields to the forward hemisphere, i.e., to above midrapidity $y_{\mathrm{cm}} = 2.9$. For the symmetric reactions p + p and Pb + Pb the total particle multiplicities can be obtained by doubling the measured forward yields. In the Pb + Pb case the two TPCs outside the magnetic field (MTPCs) were used for tracking. For the proton-induced reactions with their considerably lower charged-particle multiplicity (7.2 in p + p compared to about 1500 in central Pb + Pb) a "global" tracking through all TPCs was employed. As discussed, this is important for localizing the reaction vertex in the extended target volume in the p + p case.

For particle identification the momentum range 3.5–25 GeV/c (Pb + Pb) and 3–35 GeV/c (p + p, p + Pb) was selected. Here, the specific energy loss $\mathrm{d}E/\mathrm{d}x$ of charged particles in the TPC gas lies in the region of the relativistic rise of the Bethe–Bloch function. The $\mathrm{d}E/\mathrm{d}x$ resolution of the TPCs ($\sigma/(\mathrm{d}E/\mathrm{d}x) = 5\%$ (Pb + Pb case) and 4% (p + p case)) was sufficient to separate pions from the group of kaons and protons, but the latter two particle types could only be resolved on a statistical basis. In practice, particles in a window of $\pm 1.5\,\sigma$ around the mean kaon $\mathrm{d}E/\mathrm{d}x$ (calculated using the Bethe–Bloch function with parameters adjusted to pions and TOF-identified protons and kaons) were selected. It contains 87% of all kaons. The pion and proton contamination eliminates itself to a large extent, because only kaon pairs from ϕ-decay can contribute to the ϕ-peak in the invariant-

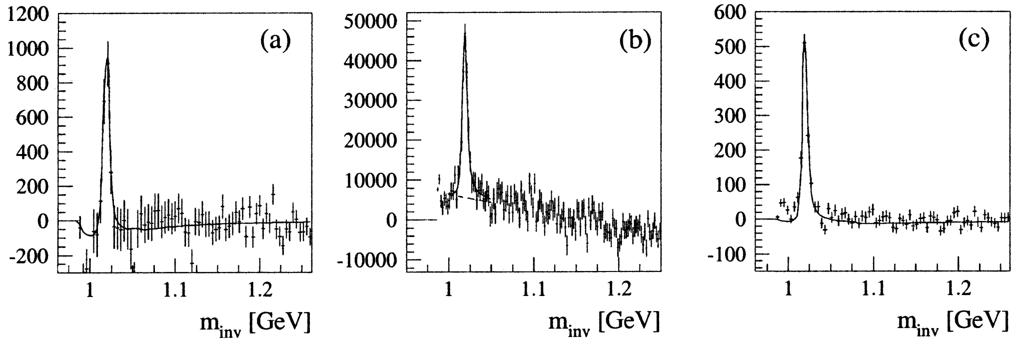

Fig. 1. Representative ϕ-signals in K^+K^- invariant-mass spectra after background subtraction. (a): Pb + Pb at midrapidity, TOF + dE/dx identification; (b): Pb + Pb, MTPC acceptance, dE/dx; (c): p + p, full acceptance, dE/dx.

mass spectrum. Misidentified particles, however, may distort the background. Near midrapidity, the combination of dE/dx and TOF information provides nearly perfect kaon separation. Here, the identification efficiency is about 85%, the contamination by pions and protons small (< 12%).

In all cases of kaon identification, the ϕ-signal was obtained by calculating the invariant mass distribution of the accepted K^+K^- pairs and subtracting the combinatorial background. The latter was reconstructed by the usual event mixing method. Both were normalized to the same number of particle pairs in the spectrum [10]. Fig. 1 shows examples. In some cases, one observes remaining background, which was subtracted. It can be shown to stem mostly from misidentified particles. The peak was then fitted with a relativistic Breit–Wigner distribution ($\Gamma_0 = 4.43$ MeV) folded with a Gaussian with adjustable width σ_m representing the spectrometer resolution. The parameters of the fit function were adjusted by a fit to the signal in the total acceptance.

The data were corrected for geometrical detector acceptance, tracking efficiency, kaon decay in flight, kaon identification efficiency, and, in the TOF case, for double hits and other losses in the scintillators. The geometrical acceptance, including losses by kaon decay, was obtained by GEANT [11] simulations using parametrized phase space distributions of isotropically decaying ϕ-mesons as input. In order to give some typical values: In the ϕ-rapidity range $3 < y < 3.8$ used for the analysis of the m_t-distribution in the Pb + Pb case it varies from 62% at $p_t < 0.3$ GeV/c to 36% at $p_t = 2$ GeV/c; for the p + p and p + Pb reactions, where all TPCs were used, the corresponding values are 80% at $p_t < 0.3$ GeV/c and 73% at $p_t = 1$ GeV/c. The tracking efficiency was determined by simulations (embedding of tracks into real events) to be close to 100% in the relevant momentum range.

Details of the analysis can be found in [12]. Preliminary reports on this work were given in [5,13,14].

3. Results

The position of the ϕ-signal in the K^+K^- invariant-mass spectrum is found at (1019.4 ± 0.2) MeV in p + p, at (1019.0 ± 0.3) MeV in p + Pb, and at (1018.7 ± 0.5) MeV in Pb + Pb. The σ_m values are (1.1 ± 0.2) MeV for p + p and (1.6 ± 0.3) MeV for Pb + Pb. As 1.0 MeV is the calculated contribution from multiple scattering in the TPC material and an additional amount depending on track density is expected from the tracking accuracy, this agrees approximately with the spectrometer resolution. Therefore, within our errors mass and width of the ϕ-peak are consistent with the free-particle values $m = (1019.41 \pm 0.01)$ MeV and $\Gamma_0 = (4.43 \pm 0.05)$ MeV [15] even in the Pb + Pb case. However, for Pb + Pb we cannot exclude a parameter combination $\Gamma_0 = 6$ MeV, $\sigma_m = 1.2$ MeV, i.e., a slightly increased width.

Transverse distributions of the ϕ are shown in Fig. 2(a). From a fit to the m_t-distribution using an exponential function $dn/(m_t\, dm_t) \propto \exp(-m_t/T)$ one

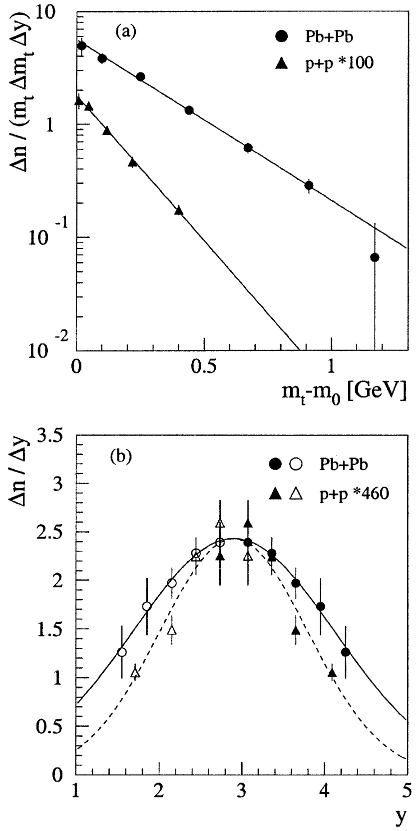

Fig. 2. (a) Transverse-mass distributions of ϕ-mesons (averaged over rapidity) for Pb + Pb ($3.0 < y < 3.8$) and p + p ($2.9 < y < 4.4$). (b) Rapidity distributions of ϕ-mesons for Pb + Pb and p + p. Full symbols represent measured points, open ones are reflected at midrapidity ($y_{\mathrm{cm}} = 2.9$).

obtains an inverse slope or temperature parameter $T = (305 \pm 15)$ MeV for Pb + Pb, to be compared with (169 ± 17) MeV for p + p. The quoted uncertainties are statistical errors. The large T-parameter in the Pb + Pb case fits into the systematics obtained for the dependence on the mass of various emitted particles (e.g., [16]). This behavior is characteristic of a transverse velocity field. Its origin is in debate; it may stem from the hadronizing partonic stage or develop in the hadronic phase [17].

The longitudinal distributions were obtained by integration over m_t in individual rapidity intervals using the slope parameter determined before (Fig. 2(b)). In the Pb + Pb case the distribution is clearly broader than in p + p and similar to that measured for other pro-

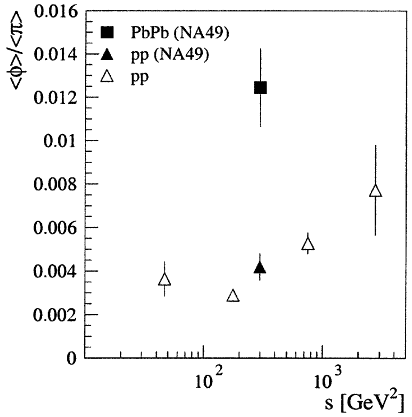

Fig. 3. ϕ/π ratio measured for Pb + Pb in comparison with p + p data (NA49 and previous work [18]) as a function of the square of the center-of-mass energy per nucleon pair. π yields in p + p were taken from [21].

duced particles, e.g., pions and kaons. From a fit with a Gaussian ($\mathrm{d}n/\mathrm{d}y \propto \exp(-(y - y_{\mathrm{cm}})^2/2\sigma_y^2)$) one obtains for the widths $\sigma_y = 0.89 \pm 0.06$ (p + p) and 1.22 ± 0.16 (Pb + Pb). This difference is remarkable in view of the fact that the shape of the distributions of charged pions and kaons is very similar in both reactions (e.g., $\sigma_y(\pi) = 1.5$ [4]).

By integrating the fit functions discussed before over the whole kinematical range one obtains for the total average ϕ-multiplicities

– for p + p (inelastic): $\langle\phi\rangle = 0.012 \pm 0.0015$,
– for Pb + Pb (central): $\langle\phi\rangle = 7.6 \pm 1.1$.

The error estimates include contributions from statistics, background and extrapolation to full phase space.

For the p + p reaction a series of data exist for comparison from other experiments [18] over a wide range of energies (Fig. 3). Our data point is consistent with the other results. For the nucleus–nucleus system the data are scarce. ϕ-production was measured at the much lower AGS energy of 13.6 A GeV [19]. For 158 A GeV preliminary data were reported by the CERN NA50 collaboration [20].

The topology dependence of the $\langle\phi\rangle/\langle\pi\rangle$ ratio in p + p as measured in this experiment is shown in Fig. 4(a). n_{ch} is the number of the emitted charged particles within the acceptance of the NA49 spectrometer (typically 80%). For p + Pb interactions the yields were obtained in four different centrality intervals (Fig. 4(b)). For the extrapolation of the mea-

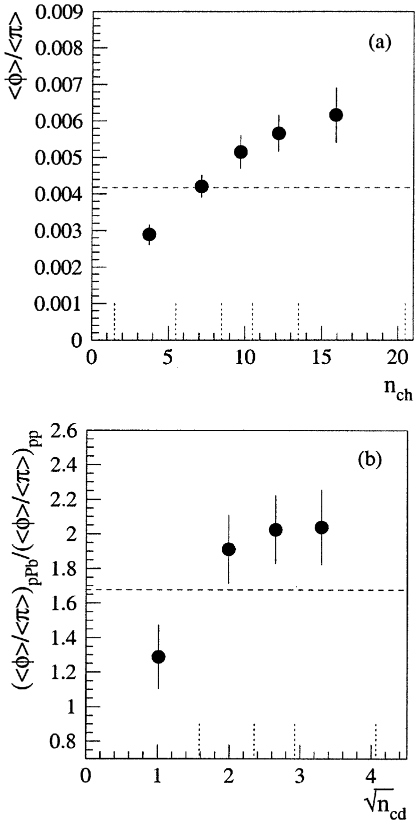

Fig. 4. (a) Multiplicity dependence of the ϕ/π ratio in $p+p$. The cross-section weighted average is indicated by the horizontal dashed line. (b) Centrality dependence of the ϕ/π ratio in the forward hemisphere in $p+Pb$ normalized to the average $p+p$ value. The minimum-bias value is indicated by the horizontal dashed line. Vertical dashed lines indicate bin sizes in the abscissa.

sured to the total forward ϕ-yield the parameters σ_y and T from $p+p$ were used. This introduces a systematic error of possibly 5 to 10%, which has to be added to the statistical errors displayed in Fig. 4(b). It has to be emphasized that the $p+Pb$ data hold for the forward hemisphere only. When comparing them with the symmetric reactions $p+p$ and $Pb+Pb$ one has to take into account two effects, (a) the feed-over of ϕ-yield from the target hemisphere which may depend on centrality, and (b) the projectile energy loss which leads to a small ($\leqslant 0.2$ rapidity units) backward shift of the projectile fragmentation center of mass.

4. Discussion

When interpreting the total ϕ-production cross section it is natural to use the emitted pions as reference. Approximately, this is equivalent to a normalization to the number of nucleons participating in the reaction as shown by data for minimum-bias $p+p$ as well as for peripheral and central $Pb+Pb$ collisions [4]. The comparison of the normalized ϕ-yield between central $Pb+Pb$ and inelastic $p+p$ gives a "ϕ-enhancement factor"

$$\frac{\langle\phi\rangle/\langle\pi\rangle\ (\mathrm{Pb+Pb\ central})}{\langle\phi\rangle/\langle\pi\rangle\ (\mathrm{p+p\ inelastic})}=3.0\pm0.7,$$

where $\langle\phi\rangle$ designates the average ϕ-multiplicity, and $\langle\pi\rangle = (\langle\pi^+\rangle + \langle\pi^-\rangle)/2$ is the corresponding quantity for pions (numerical values: 2.87 for $p+p$ [21] and 611 for $Pb+Pb$ (NA49 data)).

The enhancement factor obtained here is significantly larger than the one measured for kaons (approximately 2.0 [3,5]), but clearly smaller than in the case of $|S|=2$ and $|S|=3$ baryons [22,23]. It agrees approximately with the preliminary result of NA50 [20] for the $\phi/(\rho+\omega)$ ratio, that was found to rise by a factor of about 3 between deuteron–carbon and central $Pb+Pb$.

The magnitude of the experimental ϕ-enhancement is moderate in comparison with estimates based solely on the flavor composition in an assumed QGP. According to [7] the ϕ/ω ratio should then rise by more than an order of magnitude. As pointed out by various authors [1,24] this model neglects the influence of the hadronization process and a likely redistribution of strangeness between hadrons. Both effects are expected to reduce this enhancement considerably [24]. It has been shown [25] that for nucleus–nucleus collisions the strangeness yield is indeed consistent with that expected for QGP formation when taking into account the hadronization.

Hadro-chemical models have also been applied successfully to ϕ-production data. It has been shown [26] that the particle composition in the final state of the collision corresponds approximately to a thermal equilibrium immediately after hadronization, except for a suppression of strange particles. It is tacitly assumed that there is no change afterwards. Apparently, the hadronization process fills the available hadronic phase space. The only information remaining from the preceding partonic state is preserved in the value of the "strangeness saturation factor" γ_S. In this picture, the s-quark production in the partonic state is insufficient to support full hadrochemical equilibrium at the high temperature of the initial hadronic state. Strangeness enhancement in nucleus–nucleus as compared to $p+p$ collisions is traced back to a change of γ_S (0.45 for $p+p$ and 0.6–0.7 for nucleus–nucleus collisions). A thermodynamical model [27], which attempts to reproduce the particle composition without introduction of γ_S would favour a 1.6 times higher ϕ-yield than measured here.

Uncertainties in the interpretation of strangeness enhancement in nucleus–nucleus collisions as well as experimental facts, in particular the enhancement of strange particles already in the forward hemisphere of the $p+Pb$ reaction [5], motivate a more detailed investigation of $p+p$ and $p+Pb$ reactions. Whereas the previous discussion of $p+p$ is concerned with production cross sections in average inelastic collisions, Fig. 4(a) shows that there is already a significant variation between subgroups of $p+p$ events. In more violent collisions — defined by selecting a higher charged multiplicity n_{ch} — the ϕ/π ratio is considerably higher than on average. This is qualitatively consistent with previous observations [28] for $p+Be$ collisions. For $p+Pb$ (where we are restricted to the forward hemisphere), Fig. 4(b) demonstrates an even stronger variation as a function of $\sqrt{n_{CD}}$, which is a measure of the number of interactions of the projectile inside the target. On average, the ϕ/π ratio increases by a factor 1.7 above that in average inelastic $p+p$ collisions. Apparently, the consecutive interactions of the projectile nucleon with several target nucleons in $p+Pb$ (3.7 on average) lead to an increased ϕ-production in the forward hemisphere. Similar observations have been made for $K^{\pm}$ production [5].

5. Summary

An enhancement of a factor of 3.0 ± 0.7 was found for the ratio $\langle\phi\rangle/\langle\pi\rangle$ when comparing central $Pb+Pb$ to minimum-bias $p+p$ reactions. No change of the mass or the width of the ϕ in its K^+K^- decay channel was observed. Centrality-selected $p+p$ and $p+Pb$ collisions show a significant rise in $\langle\phi\rangle/\langle\pi\rangle$ over minimum-bias $p+p$, which, however, is smaller than that observed in central $Pb+Pb$ collisions. A model based on the assumption of a transient partonic phase with subsequent statistical hadronization is consistent with the measured $\langle\phi\rangle/\langle\pi\rangle$ enhancement in $Pb+Pb$.

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