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Hard π^0 and η production in S + Au and Pb + Pb nuclear collisions at SPS energies and the possible signature of quark–gluon plasma

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Abstract. Hard π^0 and η production is investigated in Landau and Bjorken hydrodynamical models, taking a great number of hadronic resonances (16 and 42) in the hadronic phase into account. Central and peripheral S + Au and Pb + Pb collisions are considered. We consider two different scenarios: one with quark–gluon plasma (QGP) formation and one with only hadronic gas without QGP. The Cronin effect and hard direct meson emission are taken into account. It is shown that these two scenarios give similar $p_\perp$ pion spectra, which approximately agree with experimental data for S + Au collisions obtained by the WA80 Collaboration. Therefore we conclude that it is difficult to extract proof of QGP formation from hadronic spectra. However, we also calculate the η/π^0 ratio. We show that this value agrees with experimental data only for the scenario with plasma and a phase transition for hadrons. The scenario of hadronic gas without plasma disagrees with experimental data.

1 Introduction

There is considerable interest in heavy-ion reactions at sufficiently high energies, because they provide the possibility for conditions for the transition to a deconfined state of hadronic matter, i.e. a quark–gluon plasma (QGP). Apparently direct information on this state can be obtained from photons and dileptons produced in the plasma, since their mean free path is larger than the size of the "cloud" of matter created in nuclear collisions. Unfortunately the amount of direct photons is small in comparison with the amount of photons produced in decays of π^0s and resonances (on average it is ∼5%). Therefore, at present the question about the discovery of such photons remains open. One should also be aware of the considerable contribution of thermal photons from various reactions in the hadronic phase [1,2]. Therefore investigations at higher energies (for example at LHC energies) are of interest, where, according to theoretical estimates, the thermal-photon yield from the plasma phase at large $p_\perp$ can exceed the background resulting from resonance decays [3,4].

On the other hand, it is recently shown in a series of papers [5–7] that hadron and photon spectra in S + S, S + Au and Pb + Pb collisions are similar in the scenarios with and without QGP, if a considerable number of resonant states can be generated. Therefore it is concluded that it will be difficult to discover QGP formation from $p_\perp$ spectra. In [8–10] and later in [11] it was shown that measured hadron spectra (up to $p_\perp \simeq$ 2–3 GeV/c) in S + S and S + Au collisions at SPS energies can be described by transverse hydrodynamical flow with an average transverse velocity $\langle v_\perp \rangle \simeq$ 0.4–0.5c at "freezing". The "freezing" temperature T_f is different for different hadrons, e.g. $T_\mathrm{f} \simeq 110$ MeV for pions and $T_\mathrm{f} \simeq$ 140–150 MeV for K^+s at O + Au collisions [9].

Transverse motion at nuclear collisions is of considerable interest. It should be noted that the average values of $p_\perp$ for hadrons at "freezing" are not large (∼0.4–0.5 GeV/c); the main source is soft hadrons. The collective transverse flow is generated at a late stage in the region of "freezing", and therefore it difficult to extract proof of QGP formation in the initial state from hadronic spectra.

In this paper we look at the transverse motion at nuclear collisions from another point of view. We assume that, besides longitudinal hydrodynamical motion, there is transverse motion which depends on A ($\sim A^{\alpha(p_\perp)}$) and which gives the broadening of the $p_\perp$ spectra. For the value of this broadening we use experimental data (the Cronin effect [12,13]). One can assume that this effect is not brought about by collective transverse flow but, e.g., by rescattering (by a random-walk pattern) of the initial nucleons in the nucleus (see, for example, [14]). In that case we consider "leakage" of hard hadrons from the surface at hydrodynamical expansion. One can show that π^0 and η spectra with large values of $p_\perp$ (≥2–5 GeV/c) weakly depend on the "freezing" temperature T_f in the Landau and Bjorken models (though we use the usual value $T_\mathrm{f} \sim$ 130–140 MeV). We also take hard-pion emission in chromodynamics into account. We use data on hard-pion spectra in S + Au [15] and P + P [16] collisions for comparison of the calculation with experiment. We show that the scenario with plasma and the scenario without plasma can hardly be distinguished. We use two different hydrodynamical models for the calculation of π^0 and η spectra, the Landau model [17] and the Bjorken model [18], taking 16 and 42 hadronic resonances and stable particles into account. A modified "tube" model is applied to study hard thermal-meson production from QGP and hot hadronic matter in central and peripheral S + Au and Pb + Pb collisions at SPS energies. In the region $p_\perp \geq 2\,\mathrm{GeV}/c$ we take the Cronin effect and hard collisions of initial partons into account.

We also show that, if we assume that only gas of the light components π, ρ, η, and ω is formed, then the π^0 yield is distinguished considerably in the scenarios with and without plasma, and both scenarios disagree with experiment.

In this paper we also calculate the η/π^0 ratio. For the scenario with hadronic gas without plasma it can be shown that $\eta/\pi^0 \to 1$ for a large enough $p_\perp$ ($p_\perp > 3\,\mathrm{GeV}/c$). This disagrees with experimental data for S + Au and p + p collisions, which yield $\eta/\pi^0 \simeq 0.5$–0.6 [19,20]. However, the scenario with QGP and a phase transition to hadrons, and with account taken of hard-parton collisions, gives a correct value of η/π^0 [21].

In Sect. 2 we consider hard π^0 emission in the Landau hydrodynamical model for S + Au and Pb + Pb collisions. There we also examine the hard-pion yield at the initial stage of the collisions. In Sect. 3 we consider hard-pion emission in the Bjorken hydrodynamical model. In Sect. 4 we consider hard η production and the η/π^0 ratio. In Sect. 5 conclusions are given.

2 Hard-pion emission in the Landau model and in hard collisions

For the calculation of π^0 and η spectra we use two hydrodynamical models, the Landau model and the Bjorken model, and we take 16 and 42 hadronic resonances and stable particles into account. Hadron production in the region $p_\perp \simeq 1$–$4\,\mathrm{GeV}/c$ is not a volume but a surface effect (this is not the case for photons and dileptons). This corresponds to "leakage" of quarks and gluons in the plasma phase and to "leakage" of hadrons in the hadronic phase from the surface at hydrodynamical expansion. A surface element is $2\pi R_\perp \mathrm{d}x_\parallel \mathrm{d}t = 2\mathrm{d}^4x/R_\perp$ ($R_\perp = R_\mathrm{S}$ is the radius of the S nucleus). When taking the expression for the particle flux through the surface at longitudinal hydrodynamical expansion into account, we obtain

$$E\frac{\mathrm{d}\sigma}{\mathrm{d}^3p} = \frac{g_i p_\perp 2\sigma_\mathrm{in}}{R_\perp (2\pi)^3}\int \mathrm{d}^4x \exp\left(\frac{-m_\perp \cosh(y-\eta)}{T}\right), \quad (1)$$

where g_i is the statistical weight of the particle and η is the hydrodynamical rapidity. A central collision of a light and a heavy nucleus is interpreted in the Landau model as a collision with a "tube" of mass M_tu cut from the heavy nucleus ($M_\mathrm{tu} = k_1 M_\mathrm{S}$, $k_1 = 2.54$, $M_\mathrm{S} = 32 m_\mathrm{p}$). The value M_tu corresponds to the average number of participants in the target nucleus. In experiment [15] all complete events are divided into 8 bins which correspond to different degrees of centrality. The most central events correspond to $\simeq$2.8% of the total section. For central collisions of nuclei A and B we have

$$E\frac{\mathrm{d}\sigma^\mathrm{AB}}{\mathrm{d}^3p} = E\frac{\mathrm{d}\sigma^\mathrm{pp}}{\mathrm{d}^3p}\int_0^{b_\mathrm{max}} T_\mathrm{AB}(b)\mathrm{d}^2b, \quad (2)$$

where $T_\mathrm{AB}(b)$ is the overlap integral of the nuclei and b is the shock parameter. The value $T_\mathrm{AB}(b)$ is determined by

$$T_\mathrm{AB}(b) = \int \mathrm{d}^2r_\perp T_\mathrm{A}(r_\perp) T_\mathrm{B}(|\mathbf{r}_\perp + \mathbf{b}|), \quad (3)$$

where T_A is the local nuclear thickness $T_\mathrm{A}(r_\perp) = 2n_0(R_\mathrm{A}^2 - r_\perp^2)^{1/2}$ and $n_0 = 3A/4\pi R_\mathrm{A}^2$. The value $T_\mathrm{AB}(b)$ is expressed as elliptic functions for central $b \leq R_\mathrm{Au} - R_\mathrm{S}$ and for the most peripheral events $R_\mathrm{Au} \leq b \leq R_\mathrm{Au} + R_\mathrm{S}$.

We find for the most central events $b_\mathrm{max} \simeq 0.47 R_\mathrm{S}$ and a number of participants in the target $\overline{n} \simeq 79$ (i.e., $k_1 \simeq 2.46$) and in the projectile $\overline{n} = 32$. The initial longitudinal dimension in the Landau model (with account taken of shock compression) is [4]

$$\Delta \simeq \frac{(k_1+1)2R_\mathrm{S}}{3K}\sqrt{\frac{m_\mathrm{p}}{2E_\mathrm{L}}}, \quad (4)$$

where E_L is the energy per nucleon and K is the coefficient of inelasticity ($K \simeq 1/2$). If we assume QGP production in the initial state, then we find an initial temperature $T_0 \simeq 300\,\mathrm{MeV}$ [4]. The temperature T_c of the phase transition can be found by equating the pressures of the quark phase and the hadron phase [3]. When we take the contribution of 16 resonances and stable particles in the hadronic phase (with the best statistical weight) into account, we get $T_\mathrm{c} \simeq 200\,\mathrm{MeV}$. For 42 resonances we have $T_\mathrm{c} \approx 220\,\mathrm{MeV}$. For $T > T_\mathrm{c}$ the sound velocity c^2 is close to $c^2 \equiv c_1^2 \simeq 0.3$, but after the phase transition to hadrons this value is close to $c^2 \equiv c_2^2 \simeq 0.2$ [22]. The value c^2 changes little with the temperature of the plasma ($T_\mathrm{c} \leq T \leq T_0$) and the hadronic phase ($T_\mathrm{f} \leq T \leq T_\mathrm{c}$), where $T_\mathrm{f} \simeq m_\pi$ is the final temperature, i.e. the behaviour of c^2 at the phase transition is nearly a jump. In [3] a formula for a volume element $\mathrm{d}^4x = \mathrm{d}^2x_\perp \mathrm{d}x_\parallel dt$ in the Landau model at central collisions of identical nuclei was obtained. For the "tube" model we have a more complete expression (for the hadronic phase):

$$\begin{aligned}\mathrm{d}^4x = {} & \frac{\Delta^2}{4}\pi R_\mathrm{S}^2\left(\frac{1-c_2^2}{2c_2^2}\right)^2 \\ & \times \exp\left\{-2\tau\frac{1+c_2^2}{2c_2^2}\right\}[I_0(z) + |\tau| I_1(z) \\ & - \left(\frac{k_1-1}{k_1+1}\right)\frac{c_2^2}{c_1^2}\eta\frac{I_1(z)}{\sqrt{\tau^2 - c_2^2\eta^2}}]^2 \equiv \phi(\tau,\eta,c_2^2), \quad (5)\end{aligned}$$

where $\tau = \ln(T/T_0)$, $z = \left((1-c_2^2)/2c_2^2\right)(\tau^2 - c_2^2\eta^2)^{1/2}$. For the plasma phase the value c_2^2 must be replaced by c_1^2.

Equation (1) for the pion yield relates here to quarks and gluons. Calculating the integrals

$$\int_0^{\tau_c} d\tau \int_0^{\tau/c_1} d\eta \phi(\tau, \eta, c_1^2) \exp\left(-m_\perp ch(y-\eta)\right)/T,$$

we find the quark and gluon spectra. In order to find the π^0 spectra, we use the quark and gluon fragmentation function $D(z)$, obtained by means of analysis of deep inelastic lepton–nucleon data with account taken of SU(3) sum rules [23]:

$$\begin{aligned} D(z)_{\pi^0/g} &= \frac{(1-z)^{1.5}}{2z}, \\ D(z)_{\pi^0/q} &= \frac{(D_{\pi^+/q} + D_{\pi^-/q})}{2} \\ &= \frac{9/40\sqrt{z}(11/9 - z) + 0.98(1-z)^2}{2z}, \end{aligned} \quad (6)$$

where $z = p_\perp / k_\perp$. The π^0 spectra are determined by [23]

$$\frac{dN^{\pi^0}}{p_\perp dp_\perp} = \int_{k_\perp > p_\perp} \frac{dN^{q,g}}{k_\perp dk_\perp} D(z) \frac{dk_\perp}{p_\perp}. \quad (7)$$

The calculation shows that the π^0 yield from QGP at SPS energies is small: not larger than 10% of the yield from the hadronic phase (see Fig. 1). This is caused by the relatively low initial temperature at these energies; the parton contribution with $k_\perp > P_\perp$ decreases quickly with increasing $k_\perp$.

We find the π^0 yield from the hadronic phase by calculating the integrals

$$\int_{\tau_c}^{\tau_f} d\tau \int_0^{\tau/c_2} d\eta \phi(\tau, \eta, c_2^2) \exp\left(\frac{-m_\perp \cosh(y-\eta)}{T}\right)$$

(for the calculation we use the value $K = 1/2$). The results for the scenario with QGP and experimental data [15] for the most central S + Au collisions are shown in Fig. 1. In the region $p_\perp \simeq 0.5$–$1\,\mathrm{GeV}/c$, the π^0 yield agrees with experiment, but in the region $p_\perp \geq 2$–$3\,\mathrm{GeV}/c$ the result lies lower than the data. This is caused by the Cronin effect (rescattering in the nucleus) and by hard collisions of the constituents of the initial nucleons in the nucleus at an early stage of the collisions. We calculated the hard-pion production in the first order of chromodynamics (QCD), using the parton structure function of nucleons proposed in [24] and the fragmentation function (6). We have used the gluon structure function $G(x, Q^2)$ and also the valence u_v, d_v and sea quarks structure function with $Q^2 = k_\perp^2$. The invariant cross section of hard-pion production at two-parton collisions can be written as

$$E\frac{d\sigma}{d^3p} = \int_{x_T}^{1} \frac{dy_T}{x_T} \int_{\frac{y_T}{2-y_T}}^{1} dx_1 \left(\frac{1}{\pi}\frac{d\sigma}{d\hat{t}}\right) \times \frac{D^{\pi/q,g}\left(\frac{x_T}{y_T}\right) x_1 G_A(x_1, Q^2) x_2 G_B(x_2, Q^2)}{x_1 - \frac{y_T}{2}}, \quad (8)$$

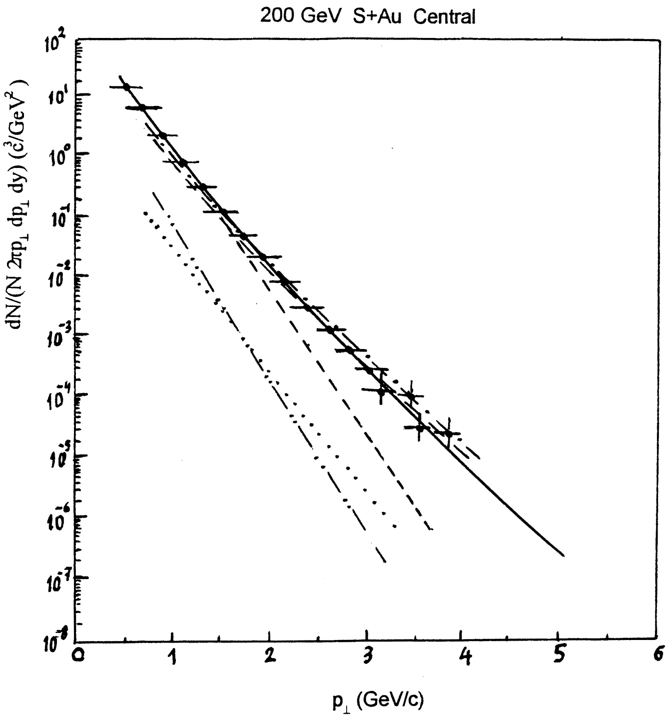

Fig. 1. π^0 emission in the Landau model. Short-dashed line: thermal-pion emission from the hadronic phase. Dotted line: thermal-pion emission from the plasma phase. Solid line: the total pion yield with the Cronin effect and hard processes for the scenario with plasma (16 resonances). Dash-dotted line: pion emission for the scenario without plasma and hard processes but with the Cronin effect (16 resonances); long-dashed line: the same but for 42 resonances. Dash-two-dotted line: pion emission from the plasma in the Bjorken model (as compared with the Landau model)

where $x_T = 2p_\perp/\sqrt{s}$, $y_T = x_T/z$, and $x_2 = x_1 y_T/(2x_1 - y_T)$. $d\sigma/d\hat{t}$ is the elementary cross section of two-parton collisions. G_A and G_B are parton structure functions in the nucleus. We took the isotopic composition of the S and Au nuclei into account, i.e. the number of u and d quarks in the proton and in the neutron, but it turned out that this gives a small effect. One can consider hard collisions of protons taking the overlap integrals in central and peripheral collisions into account. At very high energies (LHC, RHIC) the considerable contribution gives structure at small x, e.g. the sea quarks. However, at SPS energies the main contribution to the direct-pion yield is given by the collision of valence quarks and gluons: $q^{val}q^{val}$, $q^{val}g$, and gg. The sea quarks contribute no more than 3%.

The "soft" correction in QCD for pp collisions can give an increase in the π^0 yield by a k-factor of $\simeq$2 (for intermediate $p_\perp$ values) [25] . Therefore one should note that, with account taken of hydrodynamics, the π^0 yield for $p_\perp = 3\,\mathrm{GeV}/c$ agrees with experiment with an error $\leq$20% (Fig. 2), i.e. hydrodynamics gives a considerable contribution in the "soft" corrections. However, already at $p_\perp = 5\,\mathrm{GeV}/c$ the π^0 production for pp collisions ($\sqrt{s} = 20\,\mathrm{GeV}$) is practically completely determined

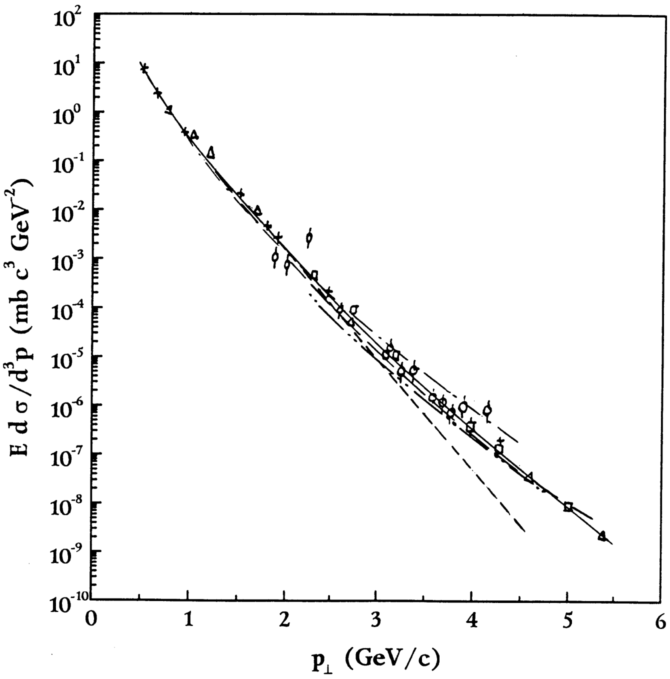

Fig. 2. The invariant cross section for the reaction $\mathrm{p+p} \to \pi + \mathrm{X}$ at $\sqrt{s} = 19.4$–$23.8\,\mathrm{GeV}$. The data and their fit (solid line) are taken from [16] (the references are in [16].) Short-dashed line: thermal π^0 emission from the hadronic phase in the Landau model with plasma without hard processes (16 resonances); long-dashed line: the same but with hard processes; dash-dotted line: the same but for the scenario without plasma and hard processes. Dash-two-dotted line: the π^0 yield for hard processes alone

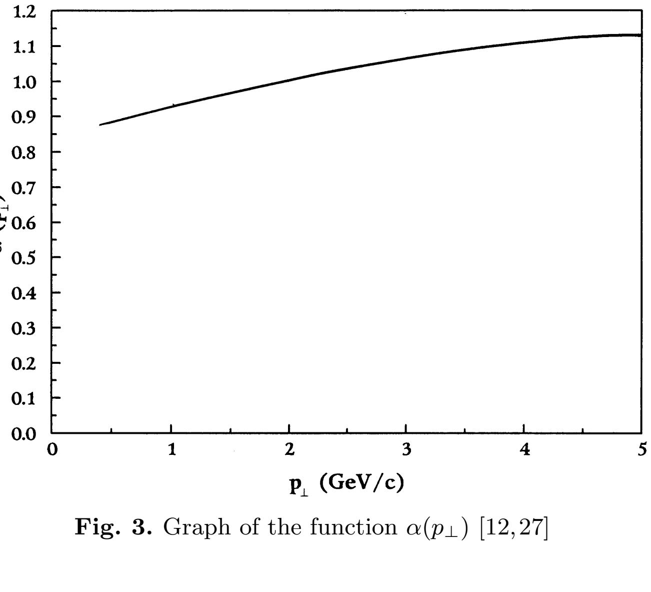

Fig. 3. Graph of the function $\alpha(p_\perp)$ [12,27]

by valence-quark collisions, and it agrees with the data (Fig. 2).

In [12] an increase with a factor of $A_{\mathrm{W}}^{\alpha(p_\perp)}$ (the Cronin effect), as compared to pp collisions, was found in the hard-pion yield in pW collisions (at 200, 300, and 400 GeV), where $\alpha(p_\perp)$ is a slowly growing function. At lower $p_\perp < 1\,\mathrm{GeV}/c$ we have $\alpha < 1$; however, at large $p_\perp$ we have already $\alpha > 1$. This is usually interpreted as an effect of multiple scattering of the incident partons [26]. For A + B collisions this effect can be generalised as follows:

$$E\frac{\mathrm{d}\sigma^{\mathrm{AB}}}{\mathrm{d}^3p} = (AB)^{\alpha(p_\perp)} E\frac{\mathrm{d}\sigma^{\mathrm{pp}}}{\mathrm{d}^3p}. \qquad (9)$$

Evidently the value $\alpha(p_\perp)$ is a practically universal function for different nuclei. In [27] the dependence of $\alpha(p_\perp)$ for π^0 data from minimum bias S + Au collisions at 200 A GeV is given. This value is close to $\alpha(p_\perp)$ found by Cronin et al. The small divergence of these values at low and high $p_\perp$ may be caused by systematic and statistical errors when comparing minimum-bias cross sections and by different normalisations of pp data. The more accurate definition does apparently not yield a decrease of $\alpha(p_\perp)$ at large $p_\perp \geq 4\,\mathrm{GeV}/c$. The function $\alpha(p_\perp)$ is shown in Fig. 3.

For the hydrodynamical "tube" model in central S+Au collisions we have: $(A_{\mathrm{Au}}A_{\mathrm{S}})^{\alpha(p_\perp)} = (\overline{n}A_{\mathrm{S}})^{\beta(p_\perp)}$, where $\overline{n}$ is the number of nucleons in the "tube". This gives $\beta = 1.11\alpha$ for $\overline{n} \simeq 79$. For example, at $p_\perp \simeq 1$, 3, and $5\,\mathrm{GeV}/c$, we have $\beta \approx 1.01$, 1.21, and 1.24, respectively. At low values of $p_\perp$, where $\alpha < 1$, the "tube" model agrees with Cronin's phenomenological descriptions, but with increasing $p_\perp$ the results become lower than the data, i.e. we must take the additional rescattering into account. Let us consider for example the π^0 yield at $p_\perp \simeq 3\,\mathrm{GeV}/c$. The contribution of additional rescattering is given by the factor $(\overline{n}A_{\mathrm{S}})^{\beta-1.01} \simeq (\overline{n}A_{\mathrm{S}})^{0.2} \simeq 4.8$ (at $\beta \approx 1$ the additional rescattering is absent). The hydrodynamical model with this factor gives (in the central interval of rapidity)

$$\frac{\mathrm{d}N^{\mathrm{S+Au}}}{2\pi p_\perp \mathrm{d}p_\perp} \simeq 0.21 \times 10^{-4} \times 4.8 \simeq 10^{-4}\,\mathrm{GeV}^{-2}. \qquad (10)$$

The π^0 yield in a hard process for the most central collisions is defined by (2). The calculation gives:

$$E\frac{\mathrm{d}\sigma^{\mathrm{S+Au}}}{\mathrm{d}^3p} = E\frac{\mathrm{d}\sigma^{\mathrm{pp}}}{\mathrm{d}^3p}(\overline{n}A_{\mathrm{S}}) \times 0.214. \qquad (11)$$

Here the value $E(\mathrm{d}\sigma^{\mathrm{pp}}/\mathrm{d}^3p)$ corresponds to the total cross section which is determined by (8). When taking the Cronin effect into account, we must multiply $\overline{n}A_{\mathrm{S}}$ with a factor of 4.8. This gives the hard contribution for central collisions ($\simeq 2.8\%\,\sigma_{\mathrm{tot}} \approx 102\,\mathrm{mb}$):

$$\frac{\mathrm{d}N^{\mathrm{S+Au}}}{2\pi p_\perp \mathrm{d}p_\perp} \simeq 2.4 \times 10^{-4}\,\mathrm{GeV}^{-2}. \qquad (12)$$

The total contribution of (10) and (12) is $\simeq 3.4 \times 10^{-4}\,\mathrm{GeV}^{-2}$, and this agrees with the data.

For the value $p_\perp = 5\,\mathrm{GeV}/c$, (8) gives the total contribution of the hard processes: $E(\mathrm{d}\sigma^{\mathrm{pp}}/\mathrm{d}^3p) \simeq 1.0 \times 10^{-8}\,\mathrm{mb\,GeV}^{-2}$. This agrees with the data and their fit [16]. When taking (11) into account with the Cronin effect, $E(\mathrm{d}\sigma^{\mathrm{S+Au}}/\mathrm{d}^3p) = E(\mathrm{d}\sigma^{\mathrm{pp}}/\mathrm{d}^3p)(\overline{n}A_{\mathrm{S}})^{\beta}0.214$ (where $\beta \simeq 1.24$), we get at $p_\perp = 5\,\mathrm{GeV}/c$:

$$\frac{\mathrm{d}N^{\mathrm{S+Au}}}{2\pi p_\perp \mathrm{d}p_\perp} \simeq 3.5 \times 10^{-7}\,\mathrm{GeV}^{-2}.$$

This agrees with the smooth continuation of the experimental curve to $p_\perp = 5\,\mathrm{GeV}/c$. Here hydrodynamics with Cronin's effect gives a contribution of <3%.

One should note that in the Landau model with a large number of resonances the mixed phase gives a considerably smaller contribution than in the Bjorken model because of the high temperature of the phase transition ($T_c \geq 200\,\mathrm{MeV}$). In the Bjorken model $T_c \simeq 160\,\mathrm{MeV}$ is usually used. The duration of the mixed phase is defined by the ratio s_q/s_h, where s_q and s_h are the entropy density in the plasma and in the hadronic phase, respectively.

Let us now consider the most peripheral S + Au collision ($\simeq$31% σ_{tot}). Here we have:

$$E\frac{\mathrm{d}\sigma^{\mathrm{S+Au}}}{\mathrm{d}^3p} = E\frac{\mathrm{d}\sigma^{\mathrm{pp}}}{\mathrm{d}^3p}\int_{b_{\min}}^{b_{\max}} T_{\mathrm{S+Au}}(b)\mathrm{d}^2b. \quad (13)$$

The calculation results in $b_{\min} \simeq 2.17R_{\mathrm{S}}$ and $b_{\max} \simeq 2.62R_{\mathrm{S}}$. One finds that the average number of collisions $\overline{n} \simeq 7.8$ and that the number of participants in the projectile $\overline{n_{\mathrm{p}}} \simeq 3.64$ and in the target $\overline{n_{\mathrm{t}}} \simeq 5.28$. Here we calculate the π^0 spectra in an analogous way as for the "tube" model in central collisions: instead of $k_1 = 2.46$ and A_{S} we write $k_1 = 5.28/3.64 \simeq 1.45$ and take a value of 3.64 for the projectile. We now have for peripheral collisions:

$$(A_{\mathrm{Au}}A_{\mathrm{S}})^{\alpha(p_\perp)} = (\overline{n} \times 3.64)^{\beta_1}, \quad (14)$$

where $\overline{n} \simeq 5.28$. Therefore we have $\beta_1 \simeq 2.96\alpha$. In the region $p_\perp \sim 1\,\mathrm{GeV}/c$ the "tube" model agrees with the data without additional rescattering. This corresponds to $\alpha \simeq 0.92$, i.e. $\beta \simeq 2.7$. This value must be subtracted from β_1. We have, e.g., at $p_\perp = 3\,\mathrm{GeV}/c$: $(\overline{n} \times 3.64)^{0.55} \approx 5.1$. The "tube" model with this factor gives

$$\frac{\mathrm{d}N}{2\pi p_\perp \mathrm{d}p_\perp} = 1.2 \times 10^{-6} \times 5.1 \simeq 6.12 \times 10^{-6}\,\mathrm{GeV}^{-2}. \quad (15)$$

The hard contribution for the most peripheral collisions is defined by (13). This gives $E(\mathrm{d}\sigma^{\mathrm{S+Au}}/\mathrm{d}^3p) = E(\mathrm{d}\sigma^{\mathrm{pp}}/\mathrm{d}^3p)$ $(\overline{n}\times 3.64)\times 12$. When we take a factor of 5.1 (Cronin effect) into account, we have

$$\frac{\mathrm{d}N}{2\pi p_\perp \mathrm{d}p_\perp} \simeq 9.9 \times 10^{-6}\,\mathrm{GeV}^{-2}. \quad (16)$$

The total contribution of (15) and (16) gives at $p_\perp = 3\,\mathrm{GeV}/c$: $\mathrm{d}N/(2\pi p_\perp \mathrm{d}p_\perp) \simeq 1.6\times 10^{-5}\,\mathrm{GeV}^{-2}$. This agrees with the data.

The π^0 spectra in peripheral S + Au collisions are shown in Fig. 4 together with the data [15]. It should be noted that when taking "leakage" across the surface of the spherical segment more exactly into account the result practically does not change.

We also use the hydrodynamical "tube" model for investigating π^0 production in the central (10% σ_{tot}) and the most peripheral (20% σ_{tot}) Pb + Pb collisions at $E_{\mathrm{L}} = 158\,\mathrm{A\,GeV}$. If we assume QGP production in the initial state, we find an initial temperature $T_0 \simeq 285\,\mathrm{MeV}$ in the Landau model at this initial energy. For central collisions

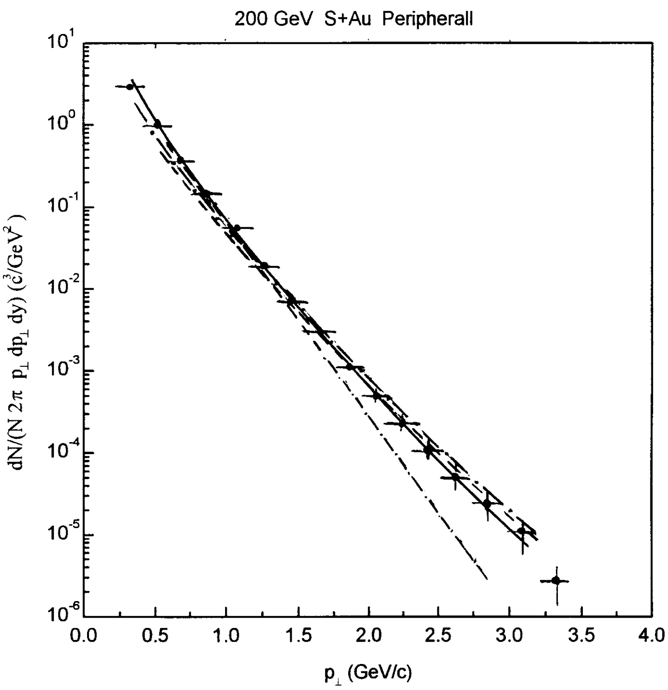

Fig. 4. Hard π^0 emission in peripheral S + Au collisions at SPS energies in the Landau model. Short-dash-dotted line: thermal-pion emission from the hadronic phase. Solid line: the total π^0 yield with the Cronin effect and hard processes for the scenario with plasma (16 resonances). Long-dash-dotted line: pion emission for the scenario without plasma and hard processes but with the Cronin effect (16 resonances); dashed line: the same but for 42 resonances. The data are taken from [15]

we find for symmetrical nuclei $b_{\max} \simeq 0.63R_{\mathrm{Pb}}$ in (2). The number of participants $\overline{n}$ was found to be $\simeq$170 in the projectile and the target. Here we have $(A_{\mathrm{Pb}}A_{\mathrm{Pb}})^{\alpha} = (\overline{nn})^{\beta}$, i.e. $\beta \cong 1.04\alpha$. In these calculations we use the same value $\alpha(p_\perp)$ as for S + Au collisions. For example at $p_\perp = 3\,\mathrm{GeV}/c$ we have $(\overline{nn})^{\beta-0.96} = (\overline{nn})^{1.14-0.96} \simeq 6.37$, where the number 0.96 corresponds to a value $\alpha \simeq 0.92$ at $p_\perp \simeq 1\,\mathrm{GeV}/c$. Hydrodynamics gives for Pb + Pb at $p_\perp = 3\,\mathrm{GeV}/c$ with account taken of the Cronin effect:

$$\frac{\mathrm{d}N}{2\pi p_\perp \mathrm{d}p_\perp} = 0.435 \times 10^{-4} \times 6.37 \simeq 2.76 \times 10^{-4}\,\mathrm{GeV}^{-2}. \quad (17)$$

The calculation gives for the π^0 yield in hard processes at central (10% σ_{tot}) Pb + Pb collisions:

$$E\frac{\mathrm{d}\sigma^{\mathrm{Pb+Pb}}}{\mathrm{d}^3p} = E\frac{\mathrm{d}\sigma^{\mathrm{pp}}}{\mathrm{d}^3p}\frac{18A_{\mathrm{Pb}}^2}{2\pi} \times 0.12 = E\frac{\mathrm{d}\sigma^{\mathrm{pp}}}{\mathrm{d}^3p}(\overline{nn}) \times 0.505. \quad (18)$$

The total cross section $E(\mathrm{d}\sigma^{\mathrm{pp}}/\mathrm{d}^3p)$ at $E_{\mathrm{L}} = 158\,\mathrm{GeV}$ is determined by (8). We have, when taking the Cronin effect (with a factor of 6.37) into account:

$$\mathrm{d}N/2\pi p_\perp \mathrm{d}p_\perp \simeq 7 \times 10^{-4}\,\mathrm{GeV}^{-2}. \quad (19)$$

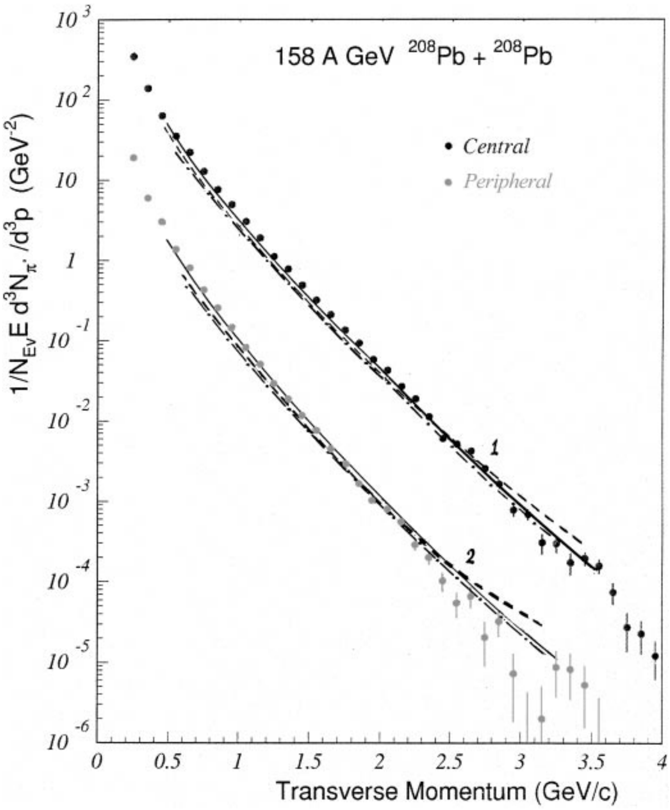

Fig. 5. Hard π^0 emission in central and peripheral Pb+Pb collisions (158 A GeV). Curves 1 and 2 correspond to central and peripheral collisions, respectively. Dashed line: π^0 emission for the scenario without plasma and hard processes but with the Cronin effect (16 components in the Landau model). Solid line: the total emission with the Cronin effect and hard processes for the scenario with QGP (Landau model, 16 components); the dash-dotted line: the same but for the Bjorken model. The data are from [28]

The total contribution of (17) and (19) at $p_\perp = 3\,\mathrm{GeV}/c$ is $\mathrm{d}N/(2\pi p_\perp \mathrm{d}p_\perp) \simeq 9.76 \times 10^{-4}$, which agrees with experiment.

For peripheral Pb + Pb collisions ($20\%\,\sigma_{\mathrm{tot}}$) we find $b_{\min} \simeq 1.6 R_{\mathrm{Pb}}$, $b_{\max} \simeq 1.84 R_{\mathrm{Pb}}$, and a number of participants in the projectile and the target $\overline{n} \simeq 8.4$. Here we have $\beta \simeq 2.56\alpha$. For example at $p_\perp = 2\,\mathrm{GeV}/c$ we have $\beta \simeq 2.56$ (at $p_\perp \simeq 1\,\mathrm{GeV}/c$ we have $\beta \simeq 2.36$). The Cronin effect gives a factor $(\overline{nn})^{0.2} \simeq 2.34$. The Landau model with this factor for peripheral Pb + Pb collisions yields:

$$\frac{\mathrm{d}N}{2\pi p_\perp \mathrm{d}p_\perp} \simeq 3.6 \times 10^{-4} \times 2.34 \simeq 0.84 \times 10^{-3}\,\mathrm{GeV}^{-2}. \quad (20)$$

The calculation for the hard processes in peripheral Pb + Pb collisions gives:

$$E \frac{\mathrm{d}\sigma^{\mathrm{Pb+Pb}}}{\mathrm{d}^3 p} = E \frac{\mathrm{d}\sigma^{\mathrm{pp}}}{\mathrm{d}^3 p} \times 10.6(\overline{nn}).$$

When we take account of the of Cronin effect (a factor of 2.34), we arrive at a π^0 yield for hard collisions ($p_\perp = 2\,\mathrm{GeV}/c$):

$$\frac{\mathrm{d}N}{2\pi p_\perp \mathrm{d}p_\perp} \simeq 5.5 \times 10^{-4}\,\mathrm{GeV}^{-2}. \quad (21)$$

The total contribution of (20) and (21) (at $p_\perp = 2\,\mathrm{GeV}/c$), $\mathrm{d}N/(2\pi p_\perp \mathrm{d}p_\perp) \simeq 1.39\,\mathrm{GeV}^{-2}$, agrees approximately with the data. In Fig. 5 we show the π^0 yield for central and peripheral Pb + Pb collisions and experimental data [28].

Let us now assume that in the initial volume no plasma but hadronic gas (16 or 42 resonances) without plasma is formed. The initial temperature T_0 can be found by equating the energy density in the initial compressed volume (at $c^2 \simeq 0.2$) and the energy density of the hadronic gas at temperature T. For S+Au collisions we find $T_0 \simeq 320\,\mathrm{MeV}$ for 16 components. If we take the decrease of the value Δ (4) for the resonance gas into account, then the π^0 yield at small $p_\perp$ (in the region $p_\perp \sim 1\,\mathrm{GeV}/c$) practically does not differ from the model with plasma. This difference is also small for 42 components (here we have $T_0 \simeq 300\,\mathrm{MeV}$). In Fig. 1 we show the π^0 yield in central S + Au collisions for the Landau model with and without plasma and experimental data. The Cronin effect and hard collisions are taken into account. It can be seen that the spectra for the two scenarios are similar.

In Fig. 4 we also show the π^0 spectra in peripheral S + Au collisions. These spectra are also similar, with only a small difference between them at small and large values of $p_\perp$.

In Fig. 5 we also show the π^0 spectra for the two scenarios in Pb + Pb collisions (for 16 components). Here we have $T_0 \simeq 300\,\mathrm{MeV}$ for the Landau model without plasma. These spectra for the two scenarios are also similar to a remarkable degree. The analogous situation takes place in the Bjorken scaling model.

3 Hard-pion emission in the Bjorken hydrodynamical model

In the Bjorken hydrodynamical model, the entropy and energy density depend on the proper time τ of the hydrodynamical element only, $\epsilon = \epsilon(\tau)$, $s = s(\tau)$, and equations of relativistic hydrodynamics give for $s(\tau)$ the solution

$$s = \frac{\mathrm{const.}}{\tau}. \quad (22)$$

Nuclear collisions at high energy are interpreted as a combination of independent NN and hh collisions, which produce cascades of secondary particles in the region of the central plateau. Every such collision is the source of a relativistic liquid, and as a result a hydrodynamical system is formed at some initial parameter τ_0 and at initial volume $V_0 = \pi R_{\mathrm{A}}^2 \tau_0$, where $\tau_0 \simeq 1\,\mathrm{fm}$. The initial energy density is defined by [18]: $\epsilon = (m_\perp / V_0)(\mathrm{d}N/\mathrm{d}y)_{y=0}$, where $m_\perp \simeq 400$–$500\,\mathrm{MeV}$ and $\mathrm{d}N/\mathrm{d}y$ can be taken from experiment. One can consider the plateau to be an approximation at the central rapidity region. In the Bjorken model the coefficient of inelasticity K is absent. Instead of

K, the experimental value $\mathrm{d}N^\pi/\mathrm{d}y$ is used. From experiments [28] we have, for very central S + Au collisions, the value $\epsilon_0 \simeq 2.9\,\mathrm{GeV/fm^3}$. If we assume that the plasma is formed in the initial volume (the gluons and three quarks), we find $T_0 \simeq 205\,\mathrm{MeV}$ (which is considerably smaller than in the Landau model). In the Bjorken model we have $\mathrm{d}^4x = \tau\mathrm{d}\tau\mathrm{d}y\mathrm{d}^2x_\perp = \tau\mathrm{d}\tau\mathrm{d}y\pi R_\mathrm{S}^2$. We consider three phases: $\tau_0 < \tau < \tau_\mathrm{Q}$ – the plasma phase, $\tau_\mathrm{Q} < \tau < \tau_\mathrm{H}$ – the mixed phase, and $\tau < \tau < \tau_\mathrm{f}$ – the hadronic phase. The entropy density in the mixed phase is

$$S = S_\mathrm{q}(T_\mathrm{c})f(\tau) + S_\mathrm{h}(T_\mathrm{c})(1 - f(\tau)), \tag{23}$$

where $f(\tau)$ is the part of the volume which is occupied by the plasma. From (22) and (23) we have

$$f(\tau) = \frac{r\tau_\mathrm{Q}/\tau - 1}{r - 1}. \tag{24}$$

Here $\tau_\mathrm{Q} = (T_0/T_\mathrm{c})^{c_1^{-2}}\tau_0$, $\tau_\mathrm{H} = (s_\mathrm{q}/s_\mathrm{h})\tau_\mathrm{Q}$, $r = \tau_\mathrm{H}/\tau_\mathrm{Q} = s_\mathrm{q}/s_\mathrm{h}$.

The π^0 yield from the plasma and from the plasma part $f(\tau)$ of the mixed phase is defined by the fragmentation function (6) and by (7). The parton production from the plasma phase is defined by:

$$\frac{\mathrm{d}N^\mathrm{part}}{2\pi k_\perp \mathrm{d}k_\perp} = \frac{g_\mathrm{part}k_\perp 2R_\mathrm{S}}{8\pi^2}\int_{\tau_0}^{\tau_\mathrm{Q}} \tau\mathrm{d}\tau \exp\left(\frac{-m_\perp}{T}\right), \tag{25}$$

where $T(\tau) = T_0(\tau_0/\tau)^{c_1^{-2}}$, $c_1^2 \simeq 0.3$. When we take the integral

$$\int_{\tau_\mathrm{Q}}^{\tau_\mathrm{H}} f(\tau)\tau\mathrm{d}\tau = (\tau_\mathrm{Q}^2/2)(r-1)$$

into account, we get an analogous contribution from the plasma part of the mixed phase:

$$\frac{\mathrm{d}N^\mathrm{part}}{2\pi k_\perp \mathrm{d}k_\perp} = \frac{g_\mathrm{part}k_\perp R_\mathrm{S}\tau_\mathrm{Q}^2(r-1)}{8\pi^2}\exp\left(\frac{-m_\perp}{T_\mathrm{c}}\right). \tag{26}$$

It should be noted that in the scaling model one can identify the rapidity y with good accuracy with the fluid rapidity η. The π^0 yield from the plasma and from the part $f(\tau)$ of the mixed phase at large $p_\perp$ is still smaller than in the Landau model (see Fig. 1). The main emission comes from the hadronic phase and the hadronic part of the mixed phase. By analogy we get the π^0 yield from the hadronic part of the mixed phase:

$$\frac{\mathrm{d}N}{2\pi p_\perp \mathrm{d}p_\perp} = \frac{g_{\pi^0}p_\perp R_\mathrm{S}\tau_\mathrm{Q}^2 r(r-1)}{8\pi^2}\exp\left(\frac{-m_\perp}{T_\mathrm{c}}\right). \tag{27}$$

We also have the π^0 yield from the hadronic phase:

$$\frac{\mathrm{d}N}{2\pi p_\perp \mathrm{d}p_\perp} = \frac{g_{\pi^0}p_\perp 2R_\mathrm{S}}{8\pi^2}\int_{\tau_\mathrm{H}}^{\tau_\mathrm{f}} \tau\mathrm{d}\tau \exp\left(\frac{-m_\perp}{T}\right), \tag{28}$$

where $T = T_\mathrm{c}(\tau_\mathrm{H}/\tau)^{c_2^2}$ and $\tau_\mathrm{f} \simeq m_\pi$

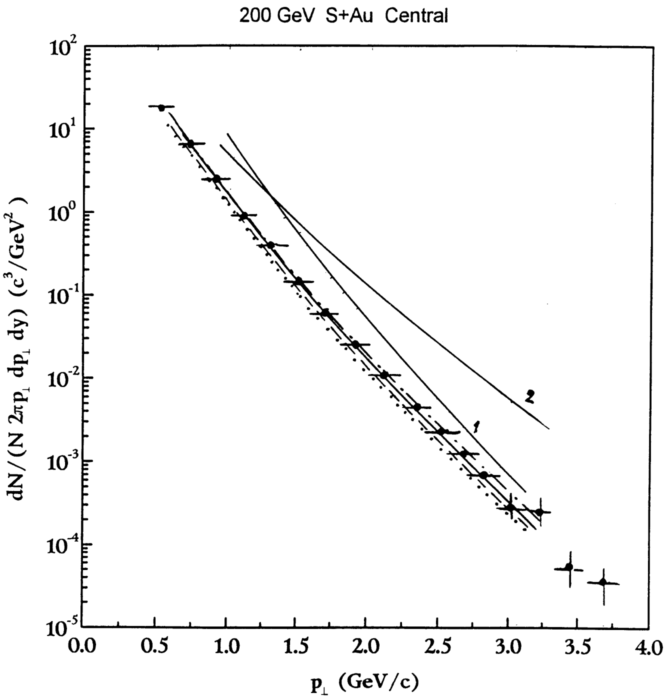

Fig. 6. π^0 emission at S + Au collisions in the Bjorken model. Solid line: the total emission with the Cronin effect and hard processes for the scenario with plasma (16 resonances); dashed line: the same emission but for 42 resonances. Dash-dotted line: the emission for the scenario without plasma and hard processes but with the Cronin effect (16 resonances); the dotted line: the same but for 42 resonances. Curves: 1 – the total pion yield for the scenario with plasma taking into account π, ρ, ω, and η only. 2 – the pion yield for the scenario without plasma and hard processes for π, ρ, ω, and η

Here we also have the jump in the value of c^2 between the hadronic and the plasma phase. In the Bjorken model we also consider two scenarios: with and without plasma for 16 and 42 resonances. Here we consider only central S+ Au collisions. The calculations show that in the scenario with plasma the total π^0 yield (with the Cronin effect and hard processes) agrees with the data (see Fig. 6). The mixed phase in the region $p_\perp \sim 1\,\mathrm{GeV}/c$ gives ~40% of the hadronic phase contribution for 16 resonances and ~30% for 42 resonances.

For hadronic gas without plasma the calculation gives the initial temperature $T_0 \simeq 230\,\mathrm{MeV}$ and $T_0 \simeq 215\,\mathrm{MeV}$ for 16 and 42 components, respectively. Here we calculated the π^0 yield analogously to (28), replacing τ_H with τ_0. Here the π^0 yield with the Cronin effect does not differ essentially from the scenario with plasma.

However, if we assume that only gas of light components π, ρ, ω, and η is formed, then the π^0 yield in the scenario with plasma differs considerably from the π^0 yield in the scenario without plasma, and both scenarios disagree with the data. This is shown in Fig. 6. Here we have $T_0 \simeq 290\,\mathrm{MeV}$ for the scenario without plasma in the Bjorken model.

Thus the scenarios with and without plasma approximately agree with the experiment for both the Landau

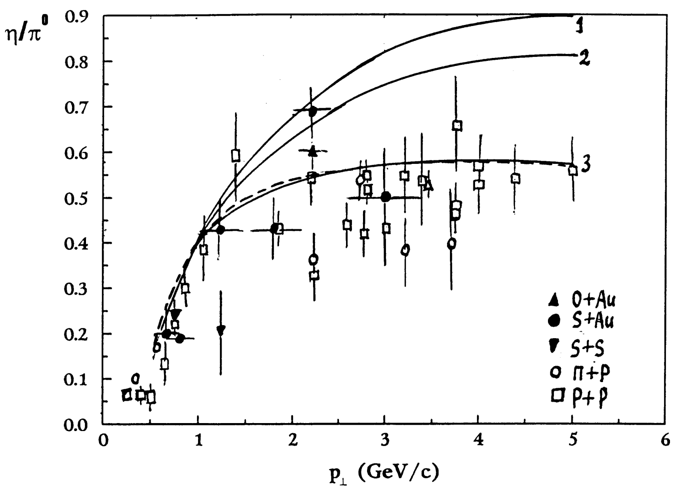

Fig. 7. The η/π^0 ratio as a function of $p_\perp$. Curves: 1 – hadronic gas with 16 and 42 resonances without plasma and hard processes for S + Au collisions (Landau and Bjorken model). 2 – the same but with hard processes and the Cronin effect. 3 – the scenario with plasma and hard processes and the Cronin effect (Landau and Bjorken models with 16 and 42 resonances). The data are taken from [19]. Dashed line: for the scenario with plasma and hard processes and the Cronin effect at Pb + Pb collisions

and the Bjorken model with a large number of resonances. Therefore it is difficult to prove the presence of a quark–gluon plasma.

Let us also consider central Pb + Pb collisions in the Bjorken model. Here we have, in the model with plasma, $T_0 \simeq 197\,\mathrm{MeV}$, $\tau_\mathrm{Q} \simeq 2\tau_0$, and $\tau_\mathrm{H} \simeq 6.4\tau_0$. We use (27) and (28), where $R_\mathrm{S} \to R_\mathrm{Pb}$. The π^0 yield for central Pb + Pb collisions in the scenario with plasma practically does not differ from the π^0 yield in the Landau model (see Fig. 5). Here the mixed phase yields ~40% of the hadron phase contribution for 16 components.

For peripheral collisions of identical nuclei in the Bjorken model we must make the replacement $R_\mathrm{Pb} \to 1.2(\overline{n})^{1/3}$, and we use the initial parameter $\tau_0 = (\overline{n}/R_\mathrm{Pb})^{1/3}\,\mathrm{fm} \approx 0.344\,\mathrm{fm}$ (for agreement with the data). The results for peripheral Pb+Pb collisions are shown in Fig. 5.

In the Bjorken model we have for the scenario of a hadron gas (16 components) without plasma $T_0 \simeq 220\,\mathrm{MeV}$. It can be shown that we have no essential difference from the scenario with plasma. However, the situation will change if we also consider η production.

4 Hard η production and the η/π^0 ratio

In a quasi one-dimensional hydrodynamical model, the mass of a hadron is contained in the factor $\exp(-(p_\perp^2 + m_i^2)^{1/2}/T)$, where $m_\pi^2 = 0.019\,\mathrm{GeV}^2$ and $m_\eta^2 = 0.3\,\mathrm{GeV}^2$. The mass contribution decreases with increasing $p_\perp$, and in the limit the ratio $\eta/\pi^0 \to 1$. In the region $p_\perp \simeq 0.5$–$1\,\mathrm{GeV}/c$, hydrodynamics gives the value η/π^0, which agrees with experiment (see Fig. 7). It is correct for scenarios with and without plasma.

However, for example for $p_\perp = 5\,\mathrm{GeV}/c$ the hydrodynamical model gives already $\eta/\pi^0 \simeq 0.9$, and for $p_\perp = 3\,\mathrm{GeV}/c$ we have $\eta/\pi^0 \simeq 0.83$ for 16 and 42 resonances. This is in contradiction with experiments for S + Au and pp collisions. Experiment [19] for S + Au at $p_\perp = 3\,\mathrm{GeV}/c$ gives $\eta/\pi^0 = 0.53 \pm 0.07$. Experiments for pp collisions [20] in the region $\sqrt{s} \simeq 23$–$62\,\mathrm{GeV}$ at $p\perp \geq 3\,\mathrm{GeV}/c$ give similar results: $\eta/\pi^0 \simeq 0.5$–0.55. Taking the Cronin effect into account does not change the ratio η/π^0 in models without plasma and hard processes (the value of $\alpha(p_\perp)$ is identical for π^0 and η production). The invariant cross sections for π^0 and η production do not indicate a visible difference of the slope of their spectra [19].

The experimental results for η/π^0 can be explained in the following way: the physical states η and η' are are mixtures of SU(3) octet and singlet states: $\eta = \eta_8 \cos\theta + \eta_1 \sin\theta$, $\eta' = -\eta_8 \sin\theta + \eta_1 \cos\theta$, where $\eta_1 =\mid 1,1\rangle = (1/\sqrt{3})(\mathrm{u\overline{u}} + \mathrm{d\overline{d}} + \mathrm{s\overline{s}})$, $\eta_8 =\mid 1,1\rangle = (1/\sqrt{6})(\mathrm{u\overline{u}} + \mathrm{d\overline{d}} - 2\mathrm{s\overline{s}})$. One can write for the η meson

$$\eta = \mathrm{s\overline{s}} \cos\theta_\eta + \frac{\mathrm{u\overline{u}} + \mathrm{d\overline{d}}}{\sqrt{2}} \sin\theta_\eta, \tag{29}$$

where $\sin\theta_\eta = \cos\theta/\sqrt{3} + \sqrt{2/3}\sin\theta$. All radiation decays are described well at $\theta \simeq 15°$. It corresponds to $\sin\theta_\eta \simeq 0.76$ and $\sin^2\theta_\eta \simeq 0.57$. For sufficiently large $z = p_\perp/k_\perp$ we have the ratio of the fragmentation function

$$\frac{D_\mathrm{q}^\eta(z)}{D_\mathrm{q}^{\pi^0}(z)} = \left[\frac{\langle \mathrm{q\overline{q}}|\eta\rangle}{\langle \mathrm{q\overline{q}}|\pi^0\rangle}\right]^2 \to \sin^2\theta_\eta \simeq 0.57$$

for any non-strange quarks [29]. The π^0 and η mesons are produced in hard collisions of non-strange quarks of identical type. At large $p_\perp$ we have $\eta/\pi^0 \simeq 0.57$, and it is evidently observed at S + Au and pp collisions. Therefore the value η/π^0 disagrees with experiment in the hydrodynamical model of hadronic gas without plasma and hard processes (see Fig. 7). Here the Landau and Bjorken models give similar results for the value η/π^0.

However, the scenario of a hadronic gas without plasma but with hard processes also disagrees with experiment (see Fig. 7). The physical cause of this is simple: in models with plasma the π^0 yield at large $p_\perp \geq 3\,\mathrm{GeV}/c$ is caused by a high temperature $T_0 > T > T_\mathrm{c}$, i.e., by the plasma region. However, the π^0 yield from the plasma is small (see Fig. 1), while emission with large $p_\perp$ (with the Cronin effect taken into account) from the hadronic phase (at $T < T_\mathrm{c}$) decreases considerably faster than the emission at hard-parton collisions. Consequently the π^0 yield at large $p_\perp \geq 3\,\mathrm{GeV}/c$ in the model with plasma is caused almost completely by hard processes and therefore the value η/π^0 agrees with experiment. However, the π^0 yield in the scenario without plasma at $T > T_\mathrm{c}$ is caused by hadronic gas and it even exceeds the yield from hard processes. Here the value η/π^0 is mainly determined by hydrodynamics and not by hard processes, and therefore it disagrees with experiment. These results and experimental data are shown in Fig. 7. It can be seen that the η/π^0 ratio agrees with the data only for the scenario with plasma and a phase transition to hadrons. We took into account, in the calculation of η/π^0, the results of hydrodynamics and of hard collisions for η and π^0; also the Cronin effect and the SU(3) mixture were taken into account.

One should note that the minimum bias data are shown in Fig. 7 for S + Au. However, the calculations show that η/π^0 for peripheral and central collisions are practically identical. In Fig. 7 we also show the η/π^0 ratio for central Pb + Pb collisions in the scenario with plasma and hard processes (Landau model with 16 resonances). This value is close to η/π^0 for S + Au collisions. However, we have no corresponding experimental data for Pb + Pb collisions.

In hydrodynamics with transverse flow the ratio η/π^0 for large values of $p_\perp$ (where $m_\perp/p_\perp \to 1$) practically only depends on the "freezing" temperature T_f and the transverse velocity β_r [10] ($\beta_\mathrm{r} = (r/R)^2\beta_\mathrm{s}$, where β_s is the velocity on the surface of the fireball). If the values T_f and β_r for π and η mesons are different, we can evidently even have $\eta/\pi^0 > 1$. This evidently disagrees with experimental data [19,20]. Therefore it is necessary to have more precise data for collisions of different nuclei at large values of $p_\perp$. Calculations of the η/π^0 ratio on the basis of the two above-mentioned models and comparison with experiment are of considerable interest.

5 Conclusion

In the present paper the Landau and Bjorken hydrodynamical models are applied to the investigation of hard π^0 and η production in S + Au and Pb + Pb nuclear collisions at SPS energies. We consider central and peripheral collisions taking into account a large number of hadronic resonances (16 and 42) in the hadronic phase. In the Landau model we use a modified "tube" model for the description of hydrodynamical expansion of a quark–gluon plasma and hadronic matter. We assume that nucleons lose on average 50% of their energy by the formation of a hot and compressed "cloud" of plasma or hadronic matter (the coefficient of inelasticity $K = 1/2$). This determines the initial energy density and temperature T_0 in this model. In the Bjorken scaling model we assume that a hydrodynamical system is formed in the initial volume V_0 at some initial parameter $\tau_0 \simeq 1\,\mathrm{fm}$ [18]. The initial energy density is defined by the value $\mathrm{d}N/\mathrm{d}y$ in the central rapidity region, which can be taken from experiment. However, for peripheral collisions it is necessary to introduce another initial parameter $\tau_0 < 1$. The sound velocity c^2 in the plasma and the hadronic phase for a large quantity of components can be calculated. Strictly speaking it changes slowly at expansion, and we use the mean quantities of c^2.

We consider two different scenarios: one with plasma (QGP) formation and one with hadronic gas without plasma. Hadron production in the region $p_\perp \simeq 1$–$4\,\mathrm{GeV}/c$ is not a volume effect but a surface effect (which is not the case for photons and dileptons). This correspond to "leakage" of partons or hadrons from the surface at hydrodynamical expansion. In the region $p_\perp \geq 2\,\mathrm{GeV}/c$ we take the Cronin effect and hard collisions of the initial partons into account. In this paper we assume that, besides longitudinal hydrodynamical motion, there is transverse motion which is dependent on A ($\sim A^{\alpha(p_\perp)}$), assuming that there is no collective transverse flow (which is absent or small in pp collisions), but there is, for example, rescattering of initial nucleons in the nucleus. This gives a broadening of $p_\perp$ spectra (the Cronin effect), for which we use the experimental data. We assume that at pp collisions mainly thermal broadening takes place. It should be noted that the value $\alpha(p_\perp)$ is practically a universal function for collisions of various nuclei.

We show that two different scenarios, with account taken of the above-mentioned effect, give similar $p_\perp$ spectra for the Landau and Bjorken models, which agree approximately with experiment. Therefore it is difficult to extract proof of QGP formation from hadronic spectra.

However, we also consider the η spectra and the η/π^0 ratio for the two models with hard-parton collisions and with the Cronin effect taken into account. This value disagrees with the data for the scenario without plasma (the η/π^0 is too large), but agrees for the scenario with plasma. This is caused by a large hard-process contribution in the scenario with plasma. Evidently it is true for different nuclei.

In this paper we assume chemical equilibrium between ηs and πs, and we leave out a possible dependence of m_η on the temperature. However, the η/π^0 ratio in the hydrodynamical model evidently agrees with experiment for small $p_\perp$ at the usual value $m_\eta = 548\,\mathrm{MeV}$. Here the temperature is the essential factor.

At SPS energies we have similar spectra for the Landau and Bjorken models. However, the situation can change for higher energies (RHIC and LHC). A considerable increase of hard-hadron production from the plasma phase is possible in the Landau model because of the high initial temperature T_0. This depends of course on the choice of the initial parameter τ_0 in the Bjorken model. These questions will be considered in further work.

It is also interesting to investigate hard π^0 and η production in various string models, where the concept of temperature is absent, for the plasma and the hadronic phase; however, there are a few free parameters.

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References

1. E. Shuryak, Li Xiong, Phys. Lett. B **333**, 311 (1994)
2. D.K. Srivastava, B. Sinha, Phys. Rev. Lett. **73**, 2421 (1994)
3. Yu.A. Tarasov, V.G. Antonenko, Z. Phys. C **66**, 215 (1995)
4. Yu.A. Tarasov, Phys. Lett. B **379**, 279 (1996)
5. J. Cleymans, K. Redlich, D.K. Srivastava, Phys. Rev. C **55**, 1431 (1997)
6. J. Sollfrank et al., Phys. Rev. C **55**, 392 (1997)
7. E. Schnedermann, U. Heinz, Phys. Rev. C **50**, 1675 (1994)

8. K.S. Lee, U. Heinz, Z. Phys. C **43**, 425 (1989)
9. K.S. Lee, U. Heinz, E. Schnedermann, Z. Phys. C **48**, 525 (1990)
10. E. Schnedermann, J. Sollfrank, U. Heinz, Phys. Rev. C **48**, 2462 (1993)
11. P. Braun-Munzinger et al., Phys. Lett. B **365**, 1 (1996)
12. Y.W. Cronin et al., Phys. Rev. D **11**, 3105 (1975)
13. D. Antreasyan et al., Phys. Rev. D **19**, 764 (1979)
14. A. Leonidov, M. Nardi, H. Satz, Z. Phys. C **74**, 535 (1997)
15. S.L. Fokin, Ph.D. thesis, Kurchatov Institute, 1998
16. G. Holker, Ph.D. thesis, University of Munster, 1993
17. L.D. Landau, Isv. AN. SSSR **17**, 51 (1953)
18. J.D. Bjorken, Phys. Rev. D **27**, 140 (1983)
19. R. Albrecht et al., WA80 Collaboration, Phys. Lett. B **361**, 14 (1995)
20. F.W. Busser et al., Nucl. Phys. B **106**, 1 (1976); E. Amaldi et al., Nucl. Phys. B **158**, 1 (1979); G. Kourkoumelis et al., Phys. Lett. B **84**, 277 (1979); J. Antille et al., Phys. Lett. B **194**, 568 (1987)
21. Yu.A. Tarasov, Phys. Lett. B **441**, 453 (1998)
22. E.V. Shuryak, O.V. Zhirov, Yad. Fiz. **21**, 861 (1975)
23. E. Reya, Phys. Rep. **69**, 195 (1981)
24. D. Duke, Y. Owens, Phys. Rev. D **30**, 49 (1984)
25. Y. Owens, Rev. Mod. Phys. **59**, 465 (1987)
26. M. Lev, B. Petersson, Z. Phys. C **21**, 155 (1983)
27. R. Albrecht et al., Eur. Phys. J. C **5**, 255 (1998)
28. M.M. Aggarwal et al., WA80 Collaboration, Nucl. Phys. A **610**, 200 (1996)
29. R.D. Field, R.P. Feynman, Phys. Rev. D **15**, 2590 (1977)