Digamma diagnostics for the mixed-phase generation at NICA

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Abstract. A novel type of diagnostics for dense and/or hot nuclear matter produced in heavy-ion collisions at NICA and similar future colliders (FAIR, etc.) is suggested. The diagnostics is based on an assumption (confirmed in many experiments worldwide) about intensive generation of light scalar mesons (σ) the consequent decay of which produces $\gamma\gamma$ pairs with the mass and width dependent upon density and temperature of the fireball produced in the collision process. Thus, measurements of the absolute yield, mass and width of the $\gamma\gamma$ signal carry valuable information about the state of fireball generated during the high-energy nuclear collision.

## 1 Introduction. Chiral symmetry restoration in hot and/or dense nuclear matter

One of the main goals of the future heavy-ion collider NICA in Dubna will be the search for signals of the phase transition between hadronic matter and quark-gluon plasma and search for new phases of baryonic matter, including the mixed phase. However, up to date one still has no full understanding for the state of dense and hot hadronic matter which is born in heavy-ion collisions, its phase and temperature distribution, etc. There is a key hypothesis about partial chiral symmetry restoration (CSR) in hot and/or dense nuclear matter inside the fireball, which is a consequence of basic principles of QCD. The CSR effect can be observed in two areas: (i) in a single hadron when it gets to be highly excited [1, 2] and (ii) in hot and/or dense nuclear matter, i.e., in medium [3–6]. In the latter case CSR occurs due to renormalization of hadron and σ-meson propagators in nuclear medium.

However the visible manifestation of both mechanisms seems to be the same: reduction of the σ-meson (and the valence quark) mass and the σ decay width into the $\pi\pi$ channel. In fact, the σ-meson mass and full width as taken from the current PDG tables [7] are M_σ = 400–550 MeV, Γ_σ = 400–700 MeV. This demonstrates a very large spread of the σ-meson basic parameters, which is highly non-typical for the light meson sector. E.g., the ρ-meson parameters are fixed with high accuracy: M_ρ = 775.26 ± 0.25 MeV, Γ_ρ = 149.1 ± 0.8 MeV. Thus, one can suggest the possible reason for such a large spread of σ-meson parameters to be not only big errors arising when extracting the σ mass and width from experimental data (due to a very large σ width) but the really different values of the σ basic parameters found in various hadronic processes. So, the σ-meson parameters as manifested in various hadronic processes depend upon the CSR degree and thus display the big variation non-typical for all other mesons. The full discussion of the σ-meson properties can be found in a recent review [8].

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The phase transition in hot matter and the temperature behavior of pseudoscalar as well as scalar meson parameters were investigated in, e.g., [3, 6]. Figure 1 illustrates the temperature dependence of M_π, M_σ and Γ_σ obtained in [6] in the framework of the effective nonlocal quark model. It is quite evident from figure 1 that the σ-meson mass and width drop strongly when the temperature approaches its critical value T_c.
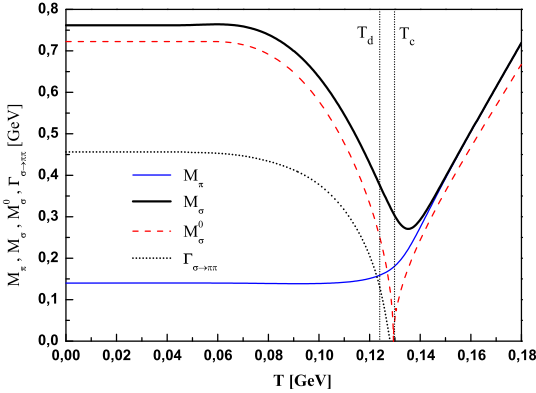
Figure 1. Temperature dependence of M_π, M_σ and Γ_σ [6]. M_σ^0 corresponds to M_σ in the chiral limit. The quark deconfinement temperature T_d and the critical temperature T_c of the chiral phase transition are also shown.

The density dependence of the σ-meson parameters has been studied in, e.g., [4, 5]. The density dependence of M_σ is essentially dictated by that of the condensate $\langle \sigma \rangle$. When the nuclear (quark) matter density becomes sufficiently high, the Pauli principle or temperature destroys the $q\bar{q}$ condensate, the valence quark motion is liberated from the condensate, and thus the CSR happens. This effect is rather similar to disappearance of superconductivity in electron gas in metals when the temperature is rising, since Cooper pairs are destroyed.

The in-medium σ-mass ansatz for the nuclear matter densities $\rho < \rho_0$ (ρ_0 being the nuclear saturated density) is $M_\sigma(\rho) = M_\sigma (1 - \alpha \rho/\rho_0)$, where M_σ is the vacuum σ-meson mass and the parameter α was found from QCD sum rules or model calculations to be $\alpha \simeq 0.2$–0.3 [4, 5]. From this ansatz, it is evident that the σ mass goes down when the matter density increases, and its width gets much reduced (due to the phase-space reduction). Thus, the σ-meson propagator in nuclear medium becomes much sharper than in vacuum due to CSR effects [5]. The overall importance of CSR can be concluded from the citation [3]: *"Observing the restoration of chiral symmetry at finite temperature is one of the central aims in the future relativistic heavy-ion experiments at the BNL RHIC and CERN LHC"*.

2 Sources for σ-meson production in hadronic collisions

Below we will review shortly some possible sources for the light scalar σ-meson production in hadronic collisions.

(i) *Dibaryon production in pn, pd and dd collisions at E ∼ 1 GeV/A*. Recent experiments of the WASA-at-COSY Collaboration [9] on the basic 2π-production reaction $pn \rightarrow d + \pi^0\pi^0$ have shown a direct correlation of the old ABC-puzzle [10] with 2π emission from the $I(J^P) = 0(3^+)$ dibaryon state $D_{03}(2380)$. The same isoscalar resonance along with ABC enhancement have been observed also in $pd \rightarrow {}^3\text{He} + \pi^0\pi^0$ and $dd \rightarrow {}^4\text{He} + \pi^0\pi^0$ [11]. So, the authors [11] concluded that "the ABC effect in the double-pionic fusion to nuclei is traced back to a *pn resonance, which obviously is strong enough to survive even in the nuclear medium*." However, the detailed mechanism of the D_{03} resonance decay which leads to the ABC enhancement is still not firmly established.

According to the dibaryon model for short-range NN interaction [12, 13], production of intermediate dibaryons in hadronic collisions is often associated with the scalar σ-meson production, with σ mass and width being renormalized strongly compared to those observed for σ mesons produced in vacuum (e.g., in $\pi\pi$ scattering). This renormalization happens due to CSR effects in the dibaryon state. Indeed, the $D_{03}(2380)$ dibaryon is a strongly excited hadron (with the excitation energy $E^* \simeq 500$ MeV), and the partial CSR was predicted for such states rather reliably [1]. Besides that, the $D_{03}(2380)$ dibaryon is a very dense object, since it has six quarks in a volume of one nucleon ($r(D_{03}) \simeq 0.7$–0.9 fm). So, the ABC effect can be interpreted as a consequence of the near-threshold σ-meson emission from the dibaryon, with the σ-meson parameters [14] $M_\sigma^{(\text{ABC})} \simeq 300$ MeV, $\Gamma_\sigma^{(\text{ABC})} \simeq 100$ MeV (cf. the σ-meson parameters found from $\pi\pi$ scattering in free space [8, 15]: $M_\sigma^{(\pi\pi)} = 441^{+16}_{-8}$ MeV, $\Gamma_\sigma^{(\pi\pi)} = 544^{+18}_{-25}$ MeV). The $\pi^0\pi^0$ invariant mass spectrum in the $pn \to d\pi^0\pi^0$ reaction at $\sqrt{s} = 2.38$ GeV calculated in the dibaryon model with the above (reduced) parameters of σ-meson is shown in figure 2 (a).
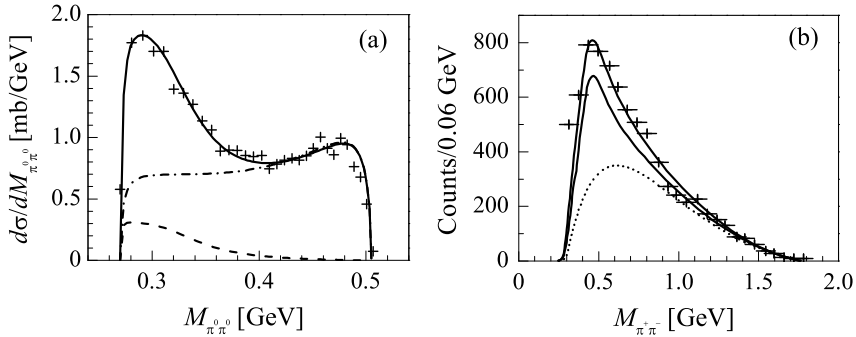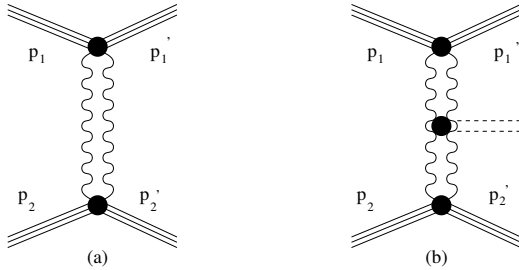

Figure 2. (a) Invariant $\pi^0\pi^0$ mass spectrum in $pn \to d\pi^0\pi^0$ at $T_p = 1.14$ GeV ($\sqrt{s} = 2.38$ GeV) [9] in comparison with the dibaryon model calculations [14] (solid line). Contributions of the near-threshold σ-meson production and the "background" process $D_{03}(2380) \to D_{12}(2150)\pi^0 \to d\pi^0\pi^0$ are shown by dashed and dash-dotted lines, respectively. (b) Invariant $\pi^+\pi^-$ mass spectrum in $pp \to pp\pi^+\pi^-$ at $p = 6.6$ GeV/c in comparison with a resonance fit (upper solid line). The 2π background without and with the contribution of the P_{11} at 1400 MeV is given by the dotted and lower solid line, respectively (for details, see [16]).

(ii) *Generation of the Roper resonance $N^*(1440)$ in NN, $N\alpha$, etc., collisions.* The authors [16] have analyzed carefully the $N^*(1440)$ generation in pp collisions at beam momenta 6–30 GeV/c and low momentum transfers $-t \leq 0.06$ GeV/c^2. The Roper resonance produced in such a way decays immediately (due to its very large width $\Gamma_{N^*} \simeq 350$ MeV) into $N\pi$ or $N\pi\pi$ channel, the latter decay going with a high probability via generation of an intermediate σ meson [7]. The $\pi^+\pi^-$ invariant mass distribution in the $pp \to pp\pi^+\pi^-$ process at 6.6 GeV/c is shown in figure 2 (b). It is clearly seen that the $\pi^+\pi^-$ production is dominated by the Roper resonance decay and is concentrated near $M_{\pi^+\pi^-} \simeq 400$ MeV corresponding to the σ-meson mass. So, the degree of CSR in the Roper resonance is less than in the dibaryon, which is likely due to the lower density of the Roper (three quarks instead of six).

(iii) *Single and double σ production from Pomeron.* It is well known that the high-energy pp scattering has a diffraction character and is governed by a Pomeron exchange. Furthermore, the Pomeron, being a scalar object, can produce σ mesons in high-energy pp collisions (see figure 3). The single and double σ emissions from Pomeron have been studied by Kisslinger et al. [17] who demonstrated that ca. 6–7% of the whole pp elastic cross section at 50 GeV goes to σ emission.

Experimental data of the GAMS Collaboration [18] on $2\pi^0$ production in high-energy pp collisions (at 450 GeV/c) revealed the high peak at $M_{\pi^0\pi^0} \simeq 500$ MeV and thus well confirmed the above Kisslinger et al. predictions (see figure 4).

Figure 3. (a) Elastic pp scattering with Pomeron exchange. (b) Peripheral σ production with double Pomeron exchange [17].
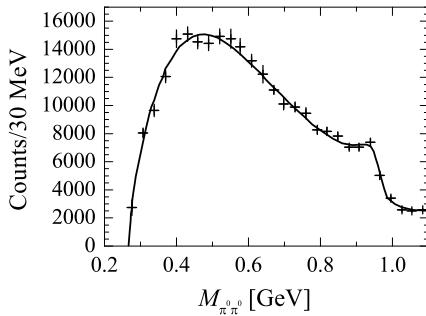
Figure 4. (a) Invariant $\pi^0\pi^0$ mass spectrum in $pp \to pp\pi^0\pi^0$ at 450 GeV/c (corrected for detection efficiency). The solid line represents the fit by an exponential-type function (for details, see [18]).

Thus, we demonstrated that in many hadronic collisions at intermediate and high energies there appears a rather high yield of light scalar σ mesons which mass and width values should carry information about the stage of CSR inside the fireball, or, in other words, about its temperature and density. In turn, this important information can be found by measuring the invariant-mass distributions of digamma signals from the σ-meson decays. Since the in-medium CSR effects lead to reduction of the σ mass and thus to suppression of the $\sigma \to \pi\pi$ decay mode, one should observe an increasing branching ratio for the $\sigma \to \gamma\gamma$ decay in hot and/or dense matter.

3 Experiments on digamma production in hadronic collisions

The initial $\gamma\gamma$-production experiments in intermediate-energy pp collisions were performed by the CELSIUS/WASA Collaboration [19]. They found a clear $\gamma\gamma$ signal at $M_{\gamma\gamma} \simeq 300$–400 MeV (see figure 5 (a)), which turned out to be very stable against cuts. Furthermore, the model which incorporated very well the $\gamma\gamma$ events from π^0, η and $\pi^+\pi^-$ production gave practically no events in the area $M_{\gamma\gamma} \simeq 300$–400 MeV, while the $\pi^0\pi^0$ production at $T_p = 1.36$ GeV gave about 15% of the observed counts between π^0 and η peaks. So, the authors [19] have come to the conclusion: "Since none of these simulated processes is able to account for the structure observed near the $\pi\pi$ threshold …, we are led to consider seriously the possibility that the observed structure (at $M_{\gamma\gamma} \simeq 300$–400 MeV) is real and might be due to the process $pp \to pp\sigma \to pp\gamma\gamma$, in particular also since $pp \to pp\pi^+\pi^-$ and $pp \to pp\pi^0\pi^0$ reactions are dominated by σ production".

Quite recently, there appeared new very encouraging $\gamma\gamma$ data with high statistics. In experiments done at the Dubna Nuclotron [20, 21], the authors analyzed the $\gamma\gamma$ spectra from pC and dC collisions at beam momenta 5.5 GeV/c (for protons) and 1.7–3.8 GeV/c per nucleon (for deuterons). The $\gamma\gamma$

yield from dC collisions at p = 2.75 GeV/cA and pC collisions at p = 5.5 GeV/c is depicted in figures 5 (b) and (c), respectively.
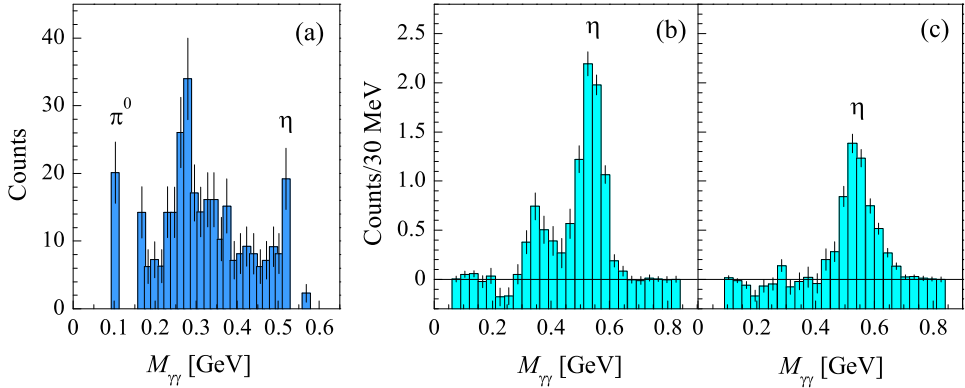
Figure 5. Invariant $\gamma\gamma$ mass spectra in (a) $pp \rightarrow pp + \gamma\gamma$ at T_p = 1.36 GeV [19], (b) dC $\rightarrow \gamma\gamma$ + X at p = 2.75 GeV/cA [20] and (c) pC $\rightarrow \gamma\gamma$ + X at p = 5.5 GeV/c [20]. The spectra in figures (b) and (c) were obtained after the background subtraction [20].

It is very interesting that the $\gamma\gamma$ signal at $M_{\gamma\gamma} \simeq 360$ MeV with the width $\Gamma_{\gamma\gamma} \simeq 60$ MeV clearly observed in dC collisions *is absent in pC collisions* (while the η meson is clearly seen in both cases). This enhancement at $M_{\gamma\gamma} \simeq 2 - 3M_\pi$ is quite similar to the ABC effect observed for near-threshold dipion production from the nucleon-nucleon and lightest nuclei collisions. So, it can be interpreted in terms of σ-meson production from the meson cloud surrounding the dibaryon component of the incident deuteron [13], see figure 6. In the kinematics of the Dubna experiment [20, 21], the possible interpretation of the above $\gamma\gamma$ signal can also be related to the well-known Landau–Pomeranchuk mechanism for bremsstrahlung in QED.
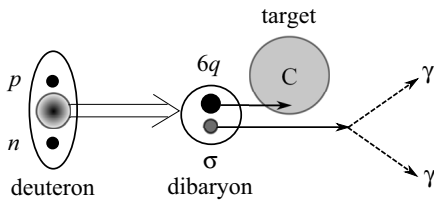
Figure 6. Dibaryon mechanism for $\gamma\gamma$ production in dC collisions.

According to Weldon [22], in hot and dense matter, due to removal of some important constraints valid in vacuum (Lorentz invariance, etc.), some processes forbidden in vacuum become possible, like the one-photon σ decay with a final dilepton production $\sigma \rightarrow \pi^+\pi^- \rightarrow \gamma \rightarrow e^+e^-$. Since the standard two-photon decay $\sigma \rightarrow \gamma\gamma$ is also valid in medium, one can relate the dilepton and digamma signals to each other. Thus, one gets two types of signals from the hot fireball, i.e., dilepton and digamma production, which carry valuable information about the state of hot matter produced in heavy-ion collisions. Recent results of the HADES Collaboration [23] seem to confirm this tight interrelation between dilepton and digamma production in heavy-ion collisions.

4 Conclusion

We have demonstrated above that in the intermediate- and high-energy collisions of nucleons and light or heavy ions a lot of light scalar σ mesons are emitted from different sources (excited hadrons,

high-energy NN collisions, etc.). Masses and widths of these σ mesons will be dependent upon the hadron excitation energy (for excited hadrons) and the temperature and density of fireball arising in heavy-ion collisions. All these σ mesons have in general a very small branching ratio for the $\gamma\gamma$ decay ($\leq 10^{-5}$). So, it would be highly uneasy to observe these digamma signals at modest temperature and density of fireball.

When, however, the temperature and/or density become sufficiently high for restoration of chiral symmetry, M_σ and $\Gamma_{\sigma\to\pi\pi}$ drop down while the $\gamma\gamma$ signal gets much higher at $M_\sigma \simeq 2M_\pi$. When $M_\sigma \to 2M_\pi$ and $\Gamma_{\sigma\to\pi\pi} \to 0$, all numerous σ mesons produced in fireball will emit the $\gamma\gamma$ pairs. So, one will observe the large $\gamma\gamma$ burst from fireball with $M_{\gamma\gamma} \simeq 2M_\pi \simeq 280$ MeV. Simultaneously, observation of such a $\gamma\gamma$ burst will be a good signal for onset of the chiral phase transition in hot and/or dense nuclear matter. Thus, measuring the invariant mass and width of the $\gamma\gamma$ signal (together with the dilepton signal) will give unambiguous information about the chiral phase transition in hot and/or dense nuclear matter. Moreover, just the combination of the dilepton and digamma signals might be very advantageous in reducing the $\gamma\gamma$ background coming from $\pi^0 \to \gamma\gamma$ decay [24].

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