Evidence for Statistical Production of J/ψ Mesons in Nuclear Collisions at 158–200A GeV

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The hypothesis of statistical production of J/ψ mesons at hadronization is formulated and checked against experimental data. It explains in a natural way the observed scaling behavior of the J/ψ to pion ratio at CERN SPS energies. Using the multiplicities of J/ψ and η mesons the hadronization temperature $T_H \approx 175$ MeV is found, which agrees with the previous estimates of the temperature parameter based on the analysis of the hadron yield systematics.

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Charmonium production in hadronic [1] and nuclear [2] collisions is usually considered to be composed of three stages: the creation of a $c\bar{c}$ pair, the formation of a bound $c\bar{c}$ state, and the subsequent interaction of this $c\bar{c}$ bound state with the surrounding matter. The first process is calculated within perturbative QCD, whereas modeling of nonperturbative dynamics is needed to describe the last two stages (see, e.g., [3] and references therein). The interaction of the bound $c\bar{c}$ state with matter causes suppression of the finally observed charmonium yield relative to the initially created number of bound $c\bar{c}$ states. This initial number is assumed to be proportional to the number of Drell-Yan pairs, which then allows for the experimental study of the charmonium suppression pattern. It was proposed [4,5] that the magnitude of the measured suppression in nuclear collisions can be used as a probe of the state of high density matter created at the early stage of the collision. The suppression of the J/ψ yield observed in $p + A$ and $O(S) + A$ collisions at 200A GeV is considered to be caused by the interactions with nucleons occurring while the primordial baryons keep interpenetrating [6]. The rapid increase of the suppression (*anomalous suppression*) observed when going from peripheral to central Pb + Pb collisions at 158A GeV [7] may be attributed to the formation of a quark-gluon plasma [8], however, alternative interpretations based on the sketched above physics picture are also under discussion [2,3,9]. In this Letter we propose a very different approach to J/ψ production in nuclear collisions based on the concept of the statistical hadron production.

It was recently found [10,11] that the mean multiplicity of J/ψ mesons increases proportionally to the mean multiplicity of pions when proton-proton ($p + p$), proton-nucleus ($p + A$), and nucleus-nucleus ($A + A$) collisions at CERN SPS energies are considered. We illustrate this unexpected experimental fact in Fig. 1, where the ratio $\langle J/\psi\rangle/\langle h^-\rangle$ is shown as a function of the mean number of nucleons participating in the interaction for inelastic nucleon-nucleon and nucleus-nucleus collisions at the CERN SPS. The $\langle J/\psi\rangle$ and $\langle h^-\rangle$ denote here the total mean multiplicities of J/ψ mesons and negatively charged hadrons (more than 90% are π^- mesons), respectively. We observe in Fig. 1 that the scaling of the $\langle J/\psi\rangle/\langle h^-\rangle$ ratio is also valid for central Pb + Pb collisions at 158A GeV, i.e., in the region of "anomalous" J/ψ suppression.

In the standard picture of the J/ψ production based on the *hard creation* of $c\bar{c}$ pairs and the subsequent *suppression* of the bound $c\bar{c}$ states the observed scaling behavior of the J/ψ multiplicity appears to be due to an "accidental" cancellation of several large effects. (Between $p + p$ interactions and central Pb + Pb collisions

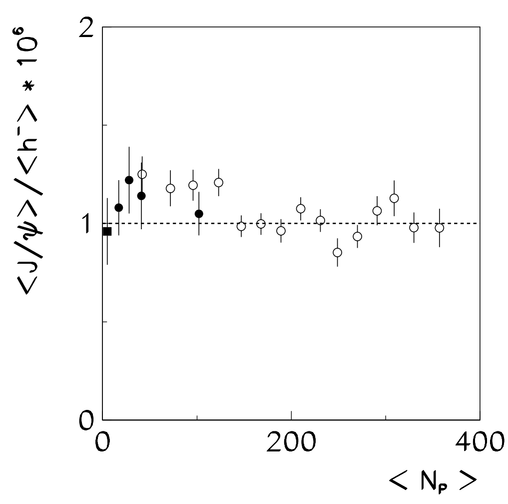

FIG. 1. The ratio of the mean multiplicities of J/ψ mesons and negatively charged hadrons for inelastic nucleon-nucleon (square) and inelastic O + Cu, O + U, S + U, and Pb + Pb (filled circles) interactions at 158A GeV plotted as a function of the mean number of participant nucleons. The results for Pb + Pb interactions measured for different centralities of collisions are shown by open circles. They are evaluated from the data of the NA50 Collaboration [7] using the procedure described in [10]. For clarity the $N + N$ point is shifted from $\langle N_P\rangle = 2$ to $\langle N_P\rangle = 5$. The dashed line indicates the value 10^{-6}.

at 158A GeV the $\langle J/\psi\rangle/\langle h^-\rangle$ ratio increases by a factor of about 5 when only the initial hard production process is considered. This increase is compensated by the suppression of J/ψ due to interactions with primordial nucleons and produced high density matter.) This motivates our effort to find an alternative production mechanism of J/ψ mesons which would explain the experimental data in a natural way.

In this Letter we show that a scaling property of the J/ψ multiplicity

$$\frac{\langle J/\psi\rangle}{\langle h^-\rangle} \cong \mathrm{const}(A) \qquad (1)$$

can be understood assuming that a dominant fraction of J/ψ mesons is produced directly at hadronization according to the available hadronic phase space.

For a long time [12] statistical models have been used to describe hadron multiplicities in high energy collisions. Thermal hadron production models have been successfully used to fit the data on particle multiplicities in $A + A$ collisions at CERN SPS energies (see, e.g., [13,14]). Because of the large number of particles a grand canonical formulation is used for the modeling of high energy heavy ion collisions [14,15]. Recently, an impressive success of the statistical model applied to hadron multiplicities in elementary $e^+ + e^-$, $p + p$, and $p + \bar{p}$ interactions at high energy was also reported [16,17]. However, in the latter case the use of a canonical formulation of the model, which assures exact conservation of the conserved charges, is necessary [15]. The temperature parameter which characterizes the available phase space for the hadron production is found in these interactions to be 160–190 MeV [16,17]. It does not show any significant dependence on the type of reaction and on the collision energy. Moreover, it coincides with the chemical freeze-out temperature estimate obtained in hadron gas models for $A + A$ collisions at the CERN SPS [13]. These facts suggest the possibility to ascribe the observed statistical properties of hadron production systematics in elementary and nuclear collisions at high energies to the statistical nature of the hadronization process [14,16–18].

Based on the above facts we formulate a hypothesis that *a dominant fraction of the J/ψ mesons produced in hadronic and nuclear collisions at CERN SPS energies is created at hadronization according to the available hadronic phase space.* J/ψ mesons are neutral and unflavored, i.e., all charges conserved in the strong interaction (electric charge, baryon number, strangeness, and charm) are equal to zero for this particle. Therefore, its production is not influenced by the conservation laws of quantum numbers. For sufficiently high collision energies, the effect of the strict energy-momentum conservation in the statistical model formulation can be neglected. Consequently, the J/ψ production can be calculated in the grand canonical approximation and, therefore, its multiplicity is proportional to the volume, V, of the matter at hadronization. Thus, the statistical yield of J/ψ mesons at hadronization is given by

$$\langle J/\psi\rangle = \frac{(2j+1)V}{2\pi^2}\int_0^\infty p^2\,dp\,\frac{1}{\exp[(p^2+m_\psi^2)^{1/2}/T_H]-1}$$
$$\cong \frac{(2j+1)V}{2\pi^2}T_H m_\psi^2 K_2\!\left(\frac{m_\psi}{T_H}\right) \cong (2j+1)V\left(\frac{m_\psi T_H}{2\pi}\right)^{3/2}\exp\!\left(-\frac{m_\psi}{T_H}\right), \qquad (2)$$

where $j = 1$ and $m_\psi \cong 3097$ MeV are the spin and the mass of the J/ψ meson and T_H is the hadronization temperature. The previously mentioned results of the analysis of hadron yield systematics in elementary and nuclear collisions within the statistical approach indicate that the hadronization temperature T_H is approximately the same for different colliding systems and collision energies. This reflects the universal feature of the hadronization process. The total entropy of the produced matter is proportional to its volume. As most of the entropy in the final state is carried by pions, the pion multiplicity is also expected to be proportional to the volume of the hadronizing matter. Thus the scaling property (1) follows directly from the hypothesis of statistical production of J/ψ mesons at hadronization and the universality of the parameter T_H. Since elements of hadronizing matter move in the overall center-of-mass system the volume V in Eq. (2) characterizes in fact the sum of the proper volumes of all elements in the collision event.

The hypothesis of statistical production of J/ψ mesons at a constant hadronization temperature T_H leads to the prediction of a second scaling property of the J/ψ multiplicity, namely

$$\frac{\langle J/\psi\rangle}{\langle h^-\rangle} \cong \mathrm{const}(\sqrt{s}\,), \qquad (3)$$

which should be valid for sufficiently large c.m. energies, $\sqrt{s}$. Figure 2 shows the ratio $\langle J/\psi\rangle/\langle h^-\rangle$ as a function of $\sqrt{s}$ for proton-nucleon interactions. The experimental data on J/ψ yields are taken from a compilation given in [19]. The values of $\langle h^-\rangle$ are calculated using a parametrization of the experimental results as proposed in [20]. Onwards from the CERN SPS energies, $\sqrt{s} \cong 20$ GeV, the ratio $\langle J/\psi\rangle/\langle h^-\rangle$ seems to saturate, in line with the expected scaling behavior (3). The rapid increase of the ratio with collision energy observed below $\sqrt{s} \cong 20$ GeV should be attributed to a significantly larger energy threshold for the J/ψ production than for the pion

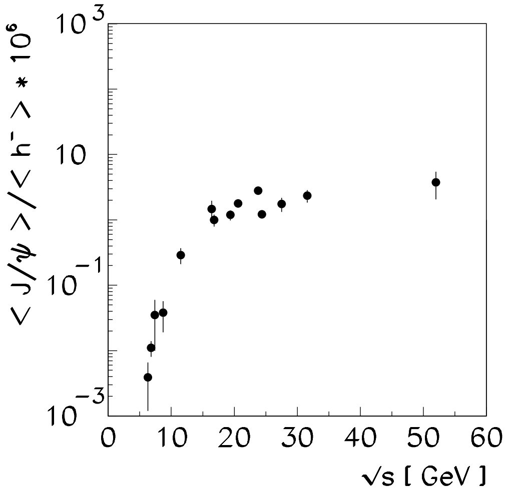

FIG. 2. The ratio of the mean multiplicities of J/ψ mesons and negatively charged hadrons for inelastic proton-nucleon interactions as a function of the collision energy in the center-of-mass system.

production. In terms of the statistical approach the effect of strict energy-momentum conservation has to be taken into account by use of the microcanonical formulation of the model. From the results presented in Fig. 2 and their discussion, follows an important conclusion that the present data on the energy dependence of J/ψ multiplicity do not contradict our hypothesis of statistical J/ψ production. However, the data at high energy are too sparse to be treated as a confirmation of the hypothesis. Possible future measurements at the CERN SPS and BNL RHIC of the energy dependence of J/ψ yield in nucleus-nucleus collisions can serve as a crucial test of our hypothesis.

The statistical J/ψ multiplicity (2) depends on two parameters, T_H and V. Assuming the fixed value of dimensionless parameter $VT_H^3 \cong 6$ in Eq. (2) we find the estimate $T_H \cong 180$ MeV from fitting with Eq. (2) the J/ψ yield in $p + p$ collisions at the CERN SPS energies. This result is in agreement with the estimates, $T_H = 191 \pm 27$ MeV and $VT_H^3 = 5.8 \pm 3.1$, obtained in Ref. [17] from the fit of the yields of light-flavored hadrons for $p + p$ collisions at $\sqrt{s} = 19.4$–19.7 GeV.

In general, the calculation of the hadron yields in the statistical model should take into account the conservation of charges and resonance feeddown contributions. However, a simple way to estimate the crucial temperature parameter in Eq. (2) from the experimental data is possible, provided that we find a second hadron which has the properties of the J/ψ meson, i.e., it is neutral, unflavored, and stable with respect to strong decays. The best candidate is the η meson. The multiplicity of η mesons seems to obey also the scaling properties (1) and (3). We note, however, that the data on η production are scarce. The independence of the $\langle\eta\rangle/\langle\pi^0\rangle$ ratio on the collision energy was observed quite a long time ago [21]. Recent data on η production suggest that the $\langle\eta\rangle/\langle\pi^0\rangle$ ratio is also independent of the size of the colliding objects. In central Pb + Pb collisions at 158A GeV the ratio $\langle\eta\rangle/\langle\pi^0\rangle = 0.081 \pm 0.014$ is measured [22]. It is consistent with the values of the ratio reported for all inelastic $p + p$ interactions at 400 GeV [23] (0.077 ± 0.005) and $S + S$ collisions at 200A GeV [24] (0.12 ± 0.04).

From the ratios $\langle J/\psi\rangle/\langle h^-\rangle$ and $\langle\eta\rangle/\langle\pi^0\rangle$ we estimate a mean ratio $\langle J/\psi\rangle/\langle\eta\rangle = (1.3 \pm 0.3) \times 10^{-5}$. Here we use the experimental ratio $\langle\pi^0\rangle/\langle h^-\rangle$ in $N + N$ interactions [25]. Under the hypothesis of the statistical production of J/ψ and η mesons at hadronization the measured ratio can be compared to the ratio calculated using Eq. (2):

$$\frac{\langle J/\psi\rangle}{\langle\eta\rangle} \cong \frac{3m_\psi^2 K_2(m_\psi/T_H)}{m_\eta^2 K_2(m_\eta/T_H)}\,, \tag{4}$$

where $m_\eta \cong 547$ MeV is the mass of the η meson. This leads to an estimate of the hadronization temperature, $T_H \approx 175$ MeV. A graphical solution of Eq. (4) is shown in Fig. 3, which illustrates the high sensitivity of the estimate of the T_H parameter by using the $\langle J/\psi\rangle/\langle\eta\rangle$ ratio. This is due to the large difference between mass of the J/ψ and the η mesons as the right-hand side of Eq. (4) is approximately proportional to $\exp[(m_\eta - m_\psi)/T_H]$.

The error of 25% on the experimental $\langle J/\psi\rangle/\langle\eta\rangle$ ratio translates into a 3 MeV error on T_H. Because of the uncertainties on the $\langle J/\psi\rangle/\langle\eta\rangle$ ratio due to the contribution from resonance decays and possible additional dynamical effects to the pure phase space calculations of hadron yields, we expect a significant systematic error

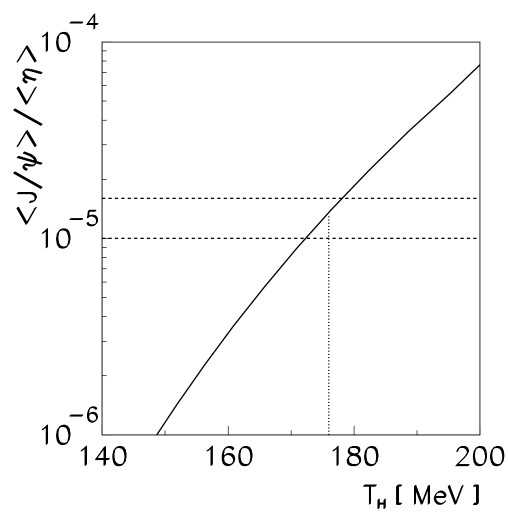

FIG. 3. The $\langle J/\psi\rangle/\langle\eta\rangle$ ratio calculated under hypothesis of the statistical production of J/ψ and η mesons at hadronization (solid line) as a function of the hadronization temperature. Band shown by dashed lines is drawn at $\pm\sigma$ around the mean experimental value of the $\langle J/\psi\rangle/\langle\eta\rangle$ ratio. The dotted line indicates $T_H = 176$ MeV.

on T_H which is, however, difficult for precise estimation. [An estimate of the fraction of the η yield from decays of heavy hadrons in $p + p$ interactions is about 50% [16], which is close to the measured fraction of J/ψ yield originating from decays (30–50%) [2,26].] We note only that a 20 MeV change of T_H causes the change of the $\langle J/\psi\rangle/\langle\eta\rangle$ ratio by a factor of about 5.

It should be pointed out that the hadron phase space calculations strongly underestimate the yield of hadron with open charm in elementary $e^+ + e^-$, $p + p$, $p + \bar{p}$ collisions. This implies that D mesons are created through hadronization of c and $\bar{c}$ produced at the early *parton* stage of the collision. Nevertheless, it was shown [16,17] that the relative abundances of open charm hadrons are in agreement with those predicted by the statistical equilibrium assumption. An assumption of the statistical coalescence (an assumption of the equilibrium hadron gas with an additional constraint of the fixed number of constituent charm quarks and antiquarks) of charm quarks and antiquarks would lead to the value of the $\langle J/\psi\rangle/\langle D\rangle$ ratio of about 0.08 for $T_H \approx 170$ MeV, which is more than 10 times higher than the ratio measured in $p + p$ collisions at $\sqrt{s} = 27$ GeV [27]. We note that, contrary to the statistical coalescence model, in our model the yield of J/ψ mesons is independent of the open charm production. Our statistical model calculation of the J/ψ multiplicity does not include possible dynamical or statistical coalescence of the initially produced $c\bar{c}$ pairs.

In summary, we show that the J/ψ production in hadronic and nuclear collisions can be understood assuming that a dominant fraction of J/ψ mesons is produced at hadronization according to the available hadronic phase space. The estimate of the hadronization temperature based on the J/ψ to η ratio, $T_H \approx 175$ MeV, agrees well with the values of the temperature parameter obtained from the analysis of the hadron yield systematics in high energy nuclear collisions. An important argument for or against the statistical mechanism of the J/ψ production proposed here would be the experimental verification of the predicted $\sqrt{s}$ scaling (3) of the $\langle J/\psi\rangle/\langle h^-\rangle$ ratio in $A + A$ collisions. This can be done by the study of the J/ψ production at low SPS energies and in the new high energy domain opened by the RHIC machine.

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[1] M. L. Mangano, hep-ph/9507353; G. A. Schuler, Z. Phys. C **71**, 317 (1996).
[2] R. Vogt, Phys. Rep. **310**, 197 (1999).
[3] L. Gerland *et al.*, Phys. Rev. Lett. **81**, 762 (1998).
[4] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).
[5] E. Shuryak, Sov. J. Nucl. Phys. **28**, 408 (1978); D. Kharzeev and H. Satz, Nucl. Phys. **A590**, 515c (1995).
[6] C. Gerschel and J. Hüfner, Z. Phys. C **56**, 171 (1992).
[7] NA50 Collaboration, M. C. Abreu *et al.*, Phys. Lett. B **450**, 456 (1999).
[8] J. P. Blaizot and J. Y. Ollitrault, Phys. Rev. Lett. **77**, 1703 (1996); H. Satz, hep-ph/9711289; D. Kharzeev, Nucl. Phys. **A638**, 279c (1998).
[9] C. Spieles *et al.*, hep-ph/9810486; hep-ph/9902337; Phys. Lett. B **458**, 137 (1999).
[10] M. Gaździcki and M. I. Gorenstein, Acta Phys. Pol. B **30**, 2705 (1999).
[11] M. Gaździcki, Phys. Rev. C **60**, 054903 (1999).
[12] E. Fermi, Prog. Theor. Phys. **5**, 570 (1950); L. D. Landau, Izv. Akad. Nauk SSSR **78**, 51 (1953); R. Hagedorn, Suppl. Nuovo Cimento **3**, 147 (1965).
[13] J. Rafelski, Phys. Lett. B **262**, 333 (1991); J. Cleymans and H. Satz, Z. Phys. C **57**, 135 (1993); J. Sollfrank, M. Gaździcki, U. Heinz, and J. Rafelski, Z. Phys. C **61**, 659 (1994); J. Letessier *et al.*, Phys. Rev. D **51**, 3408 (1995); Phys. Rev. C **59**, 947 (1999); P. Braun-Munzinger *et al.*, Phys. Lett. B **365**, 1 (1996); G. D. Yen and M. I. Gorenstein, Phys. Rev. C **59**, 2788 (1999).
[14] F. Becattini, M. Gaździcki, and J. Sollfrank, Eur. Phys. J. C **5**, 143 (1998).
[15] J. Rafelski and M. Danos, Phys. Lett. B **97**, 279 (1980).
[16] F. Becattini, Z. Phys. C **69**, 485 (1996).
[17] F. Becattini and U. Heinz, Z. Phys. C **76**, 269 (1997).
[18] R. Stock, Phys. Lett. B **456**, 277 (1999).
[19] G. A. Schuler, CERN-TH.7170/94.
[20] M. Gaździcki *et al.*, Mod. Phys. Lett. A **6**, 981 (1991).
[21] G. Donaldson *et al.*, Phys. Rev. Lett. **40**, 684 (1978).
[22] T. Peitzmann *et al.*, in Proceedings of ICHEP98, Vancouver, 1998 (to be published).
[23] M. Aguilar-Benitez *et al.*, Z. Phys. C **50**, 405 (1991).
[24] R. Albrecht *et al.*, Phys. Lett. B **361**, 14 (1995).
[25] M. Gaździcki and O. Hansen, Nucl. Phys. **A528**, 754 (1991).
[26] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **79**, 578 (1997).
[27] F. Becattini (private communication).