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NUCLEAR STRUCTURE FUNCTIONS AND J/ψ MESON YIELD SUPPRESSION IN NUCLEAR COLLISIONS

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Recently, the substantial ($\simeq$ 36%) suppression of the ratio of the J/ψ - particles yield to the background of $\mu^+\mu^-$ pairs has been observed by the NA-38 group at the CERN in central ($E_T > 50$ GeV) collisions of oxygen nuclei and uranium in comparison with peripheral ones ($E_T < 28$ GeV) /1/. This suppression is now considered as a signal of the quark-gluon plasma formation /2/. In this paper we will show that a certain part of this suppression can be explained by the difference of quark-gluon structure of the nucleus and that of a free nucleon (like the EMC-effect), i.e., by the increase of quark-antiquark pair sea in the region of $x \simeq m_\psi/\sqrt{s} \simeq 0.16$ and decrease of gluon sea responsible for J/ψ-particle production.

In papers /3,4/ it was shown that QCD evolution equations in the leading twist approximation give a simple relation between the nuclear structure functions (normalized to the mass number A) and that of a free nucleon:

$$x F_{3A}(x,Q^2) \simeq V_A(x,Q^2) = \int_x^A d\alpha\, T_A^{NS}(\alpha)\, V_N\left(\frac{x}{\alpha}, Q^2\right) \qquad (1)$$

for a nonsinglet channel (valence quark) and

$$F_{2A}(x,Q^2) \simeq \Sigma_A(x,Q^2) = \int_0^A d\alpha\, T_A^{S}(\alpha)\, \Sigma_N\left(\frac{x}{\alpha}, Q^2\right) \qquad (2a)$$

$$G_A(x,Q^2) = \int_0^A T_A^{S}(\alpha)\, G_N\left(\frac{x}{\alpha}, Q^2\right) d\alpha \qquad (2b)$$

for distribution functions of singlet quarks $\Sigma = \sum_f x\,(q_f(x) + \bar{q}_f(x))$ and gluons $G(x)$. The conservation of the baryon number and energy-momentum requires that

$$\int_0^A T_A^{NS}(\alpha)\, d\alpha = 1 \qquad \text{and} \qquad \int_0^A \alpha\, T_A^{S}(\alpha)\, d\alpha = \frac{M_A}{A M_N} \simeq 1. \qquad (3)$$

The EMC-effect in this language means that effective nonsinglet, T^{NS}, and singlet, T^{S}, nucleon distribution functions in nuclei are not identical

$$\int_0^A \left(T_A^S(\alpha)-T_A^{NS}(\alpha)\right)d\alpha=\Delta_A>0;\quad \int_0^A \alpha\left(T_A^S(\alpha)-T_A^{NS}(\alpha)\right)d\alpha=\delta_A\simeq\Delta_A>0 \tag{4}$$

Δ_A being of an order of several hundredths.

The relations (I) and (2) well describe recent experimental data on the structure-function ratio of the nucleus and deuterium /3/, especially the data of the BCDMS group /5/ which are the most precise in statistical and systematical errors, in the whole region of X except for, may be, of very small $X < 0.05$, where the shadowing effects, that are not taken into account by the leading twist approximation, can be essential. (Besides, these relations naturally explain the unusual behaviour of K^+ to K^- yield ratio in the nucleus fragmentation region /6/ for $X \gtrsim 1$).

In the following, we shall need in the estimates of the EMC-effect for quarks, antiquarks and gluons in a small X region $x \simeq m_\psi/\sqrt{s} \simeq 0.16$ (i.e. for $\sqrt{s} \simeq 20$ GeV). It is possible to obtain them by writing the relations (1),(2) in the form:

$$\Phi_A = N_A \otimes \Phi_N + \tilde{N}_A \otimes \tilde{\Phi}_N ,$$

where

$$N_A=\frac{1}{2}\left(T_A^S+T_A^{NS}\right),\quad \tilde{N}_A=\frac{1}{2}\left(T_A^S-T_A^{NS}\right)$$

and $\Phi_N = G$, $\tilde{Q}=O/2$, $Q=V+O/2$ are distribution functions of the corresponding parton momenta. Using the expansion of $\Phi_N\left(\frac{x}{\alpha}\right)$ and $\tilde{\Phi}\left(\frac{x}{\alpha}\right)$ in the vicinity of $\alpha \simeq 1$, where the effective nucleon distribution functions N_A or $\tilde{N}_A$ have a maximum

$$\int_x^A N(\alpha)\,\Phi_N\left(\frac{x}{\alpha}\right)d\alpha \simeq \langle N_A\rangle\,\Phi_N(x)+\langle(1-\alpha)N_A\rangle\, x\,\Phi_N'(x)+\dots$$

and the conditions (3) and (4) reformulated in terms of N and $\tilde{N}$

$$\langle N_A\rangle=\int_0^A N_A(\alpha)d\alpha = 1+\frac{\Delta_A}{2} \qquad \langle\tilde{N}_A\rangle=\Delta_A/2$$

$$\langle\alpha N_A\rangle=\int_0^A \alpha N_A(\alpha)d\alpha = 1-\frac{\Delta_A}{2} \qquad \langle\alpha\tilde{N}_A\rangle=\Delta_A/2 ,$$

it is easy to obtain for $\mathcal{E}_\Phi(x)=\Phi_A(x)/\Phi_N(x)-1$

$$\begin{aligned}
\mathcal{E}_A^Q(x) &\simeq \Delta_A\left(1+\frac{V}{O}+\frac{O'}{O}x+2\frac{V'}{O}\right)\cdot\left(1+2\frac{V}{O}\right)^{-1}\simeq 0.3\,\Delta_A\\
\mathcal{E}_A^{\tilde{Q}}(x) &\simeq \Delta_A\left(1+\frac{V}{O}+\frac{O'}{O}x\right)\simeq 2.5\,\Delta_A\\
\mathcal{E}_A^G(x) &\simeq \Delta_A\left(1+\frac{G'}{G}x\right)\simeq -0.9\,\Delta_A .
\end{aligned}\tag{5}$$

The latter equalities correspond to $X \simeq 0.16$, the parametrizations of valence and sea quarks being used from the "Particle data booklet-1986" and $G(x)\sim(1-x)^{10}$. (The latter was obtained from production of direct γ-quanta with high K_T and from the QCD analysis of BCDMS data /7/). Thus, the muon-pair production on the nucleus due to quark-antiquark annihilation in the central region, $y^* \simeq 0$, is enchanced as compared to nucleon-nucleon collisions and J/ψ -creation due to gluon fusion is suppressed. The values of Δ_A were obtained in /3/ by fitting SLAC data /8/ and are equal , e.g., $\Delta_{O^{16}}=0.03$, $\Delta_{Pb}=0.059$, $\Delta_U=0.066$, i.e., the J/ψ yield suppression relative to the background of $\mu^+\mu^-$ in pA collisions is $\mathcal{E}_A^G-\frac{1}{2}\left(\mathcal{E}_A^Q+\mathcal{E}_A^{\tilde{Q}}\right)$.

To explain the J/ψ-suppression due to this mechanism in the central nucleus-nucleus collisions ($E_T > 50$ GeV), as compared to the peripheral ones ($E_T < 28$ GeV), one has to suggest that the change of the nuclear quark structure is connected with the multiparticle correlation (clusters or multiquark states) whose probability increases with increasing density (i.e. with increasing E_T).

For the ratio of J/ψ-yields in the events with high and low E_T it is possible to write

$$R_\psi=\frac{\nu_{NN}^{>}+\nu_{CN}^{>}\frac{G_C(x_1)}{G_N(x_1)}+\nu_{NC}^{>}\frac{G_C(x_2)}{G_N(x_2)}+\nu_{CC}^{>}\frac{G_C(x_1)}{G_N(x_1)}\frac{G_C(x_2)}{G_N(x_2)}}{\text{(the same with } \nu^{>}\to\nu^{<}\text{ replacement)}} ,$$

where $\nu^{\gtrless}$ are the relative contributions to the production cross sections[x] of nucleon-nucleon, nucleon-cluster, cluster-nucleon and

x) For determining the cross sections of rare processes we use an approach suggested in paper/9/.

cluster-cluster interactions with $E_T > 50$ GeV and $E_T < 28$ GeV in collisions of nuclei A and B, G_C and G_N are respectively the gluon structure functions of a cluster and a free nucleon, $x_1 = m_\psi e^{y^*}/\sqrt{s}$, $x_2 = m_\psi e^{-y^*}/\sqrt{s}$ are the momentum fractions of partons of the nucleus A and that of B, y^* is the J/ψ-particle rapidity in the c.m.s. of a nucleon-nucleon collision.

One can express the ratio G_C/G_N through the quantities defined in (5) writing G_A in the form $(1-P_A)G_N + P_A G_C$, where P_A is the probability to observe a cluster in the nucleus A or the total fraction of all interactions (at all E_T) with the cluster:

$$P_A = \frac{\nu_{CN} + \nu_{CC}}{\Sigma \nu}, \qquad P_B = \frac{\nu_{NC} + \nu_{CC}}{\Sigma \nu} \tag{6}$$

$$\frac{G_C}{G_N} = \frac{\mathcal{E}_A^G}{P_A} + 1 = \frac{\mathcal{E}_B^G}{P_B} + 1. \tag{7}$$

Using this relation we immediately get $(\nu_{CC} \simeq \nu_{NC}\nu_{CN}/\nu_{NN})$

$$R_\psi = \frac{\left(1 + \frac{P_A^>}{P_A}\mathcal{E}_A^G(x_1)\right)\cdot\left(1 + \frac{P_B^>}{P_B}\mathcal{E}_B^G(x_2)\right)}{(\text{the same with } P^> \to P^<)} \cdot \frac{\Sigma \nu^>}{\Sigma \nu^<}, \tag{8}$$

where $P_{A,B}^{\gtrless}$ are the total probabilities of interactions with the cluster in nuclei A or B in the events with high or low E_T (see (6)).

Analogously, one can easily obtain the expression for Drell-Yan pair yield ratio at $x_1 = x_2 = x$ $(y^* \simeq 0)$

$$R_{\mu\mu} = \frac{\left[\left(1 + \frac{P_A^>}{P_A}\mathcal{E}_A^Q\right)\left(1 + \frac{P_B^>}{P_B}\mathcal{E}_B^{\tilde{Q}}\right) + Q \rightleftarrows \tilde{Q}\right]}{\left[\text{the same with } P^> \to P^< \text{ replacement}\right]} \cdot \frac{\Sigma \nu^>}{\Sigma \nu^<} \tag{9}$$

The ratio of expression (8) to (9) gives the relative J/ψ-suppression as compared to the background in the events with high and low E_T. Neglecting small values $\mathcal{E}_A \cdot \mathcal{E}_B$ we finally obtain

$$R = \frac{R_\psi}{R_{\mu\mu}} = 1 + \left(\frac{P_A^> - P_A^<}{P_A}\right)\left[\mathcal{E}_A^G - \frac{1}{2}\left(\mathcal{E}_A^Q + \mathcal{E}_A^{\tilde{Q}}\right)\right] + (A \to B). \tag{10}$$

The numbers of interactions $\nu^{\lessgtr}$ were calculated by the Monte-Carlo simulation of interactions of nuclei ^{16}O and ^{238}U by using the dual parton [10] and exact Glauber's relations between the cross-sections of various nucleus-nucleus processes. The nuclear densities were parametrized in the form $\rho = \rho_0 \cdot [1 + \exp(\frac{r - R_A}{d})]^{-1}$, $R_A = 1.07\, A^{1/3}$ Fm, d= 0.545 Fm. That approach describes the E_T distributions rather well in the whole observed region. (For a more detailed description of the method see the paper [11]). In addition, it was assumed that any group of two or more nucleons was considered as a cluster, if the distance between their centers was less than r_c. It appears, however, that the quantities in the paranthesis $(\cdots)$ of expressions (10) weakly depend on the value of r_c and with changing r_c from 1 Fm to 0.6 Fm they increase from 0.25 to 0.27 for oxygen and from 0.32 to 0.37 for uranium. Calculating expressions in parenthesis of (10) we obtain finally that the J/ψ-suppression is approximately 6.6-7.6 %.

Thus, we see that the suggested mechanism of changing quark-gluon structure of nucleus is a small ($\simeq 7\%$) correction to the observed by NA-38 J/ψ-suppression in nucleus-nucleus collisions. Some part of the suppression can be connected with the meson absorption in nuclear matter [12]. Calculations [12] show that in the central region $y^* \simeq 0$ it is about 15 %. Besides it is argued [13] that the essential part ($\simeq$ 25%) of J/ψ can be absorbed in the hadron (mainly, in the pion) phase produced in collisions of nuclei. If so, almost nothing is left for the signal of quark-gluon plasma. However, a more detailed investigation both of the suggested alternatives and the resonance-suppression phenomenon itself, in particular, its behaviour with changing y^* and the atomic number, is necessary.

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Ефремов А.В. и др. E2-88-498
Ядерные структурные функции и подавление выхода J/Ψ мезонов при соударении ядер

Показано, что часть эффекта подавления выхода J/Ψ мезонов /около 1/5/, обнаруженного группой NA-38 при соударении ядер O^{16} и U^{238} и рассматриваемого как сигнал кварк-глюонной плазмы, может быть объяснена различием кварк-глюонной структуры ядра и свободного нуклона /типа эффекта ЕМС/: увеличением доли кварков и антикварков и уменьшением доли глюонов в области $x \approx m_\psi/\sqrt{s}$, $(y^* \simeq 0)$.

Работа выполнена в Лаборатории теоретической физики и в Лаборатории вычислительной техники и автоматизации ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1988

Efremov A.V. et al. E2-88-498

Nuclear Structure Functions and J/Ψ Meson Yield Supperession in Nucrear Collisions

It is shown that a part of J/Ψ meson yield suppression (about 1/5), observed by the NA-38 group in central collisions of nuclei ^{16}O and ^{238}U and considered as a signal of the quark-gluon plasma, can be explained by the difference between the quark-gluon structure of the nucleus and that of a free nucleon (like the EMC-effect), namely by the increase of quark-antiquarks and decrease of gluons in the region $x \approx m_\psi/\sqrt{s} \approx 0.16$, $(y^* \approx 0)$.

The investigation has been performed at the Laboratory of Theoretical Physics and Laboratory of Computing Techniques and Automation, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1988

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