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χ_{cJ} Suppression Related to Dissociation Cross Sections by Nucleons *

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Abstract Nucleon-χ_{cJ} dissociation cross sections obtained in the quark exchange mechanism are applied to study χ_{cJ} suppression in hadronic matter created in central Pb + Pb and S + Pb collisions. Thermal average of the product of the dissociation cross section and the relative velocity of nucleon and χ_{cJ} is discussed. The survival probabilities of χ_{cJ} in the central Pb + Pb and S + Pb collisions show that the suppression caused by the collisions with nucleons and antinucleons is appreciable.

Key words dissociation cross section, thermal average, suppression

1 Introduction

J/ψ production and suppression in high energy nucleus-nucleus collisions have been studied for more than two decades. Various theoretical analyses such as nucleon energy loss in the initial state interaction[1], and J/ψ collisions with hadronic or partonic secondaries[2,3] are interesting in explaining the "anomalous" J/ψ suppression observed by the NA50 Collaboration in Pb + Pb collisions at the CERN-SPS energy[4]. Some people assume that, once the density of produced particles exceeds some critical value, the formation of a "deconfined phase" takes place[5—7]. Such work is based on the idea that the J/ψ suppression can probe the deconfined phase[8]. In order to clearly realize the suppression in the deconfined phase, the J/ψ suppression in hadronic matter has to be separated out. Since about 34.5% of the total J/ψ comes from χ_{cJ} decays[9], the χ_{cJ} suppression in hadronic matter needs to be understood. But it is less known up to now and will be studied in the present work.

As is well known, color-octet and color-singlet $c\bar{c}$ pairs are created at the very beginning of high-energy nucleus-nucleus collisions. These $c\bar{c}$ pairs transit into physical resonances of J/ψ, χ_{cJ} and ψ' with certain probabilities respectively. In the path of $c\bar{c}$ propagation, the $c\bar{c}$ pairs interact with the nucleons of both target and projectile nuclei, and also with the other particles produced in collisions. J/ψ absorption cross sections due to the inelastic collisions with light mesons (π) were obtained by Martins, Blaschke and Quack[10]. In Ref.[11], charmonium dissociations due to gluons in deconfined partonic system and pseudoscalar-octet and vector-nonet mesons in hadronic matter were studied in a QCD-based potential model. Inspired by the recently increasing interest on measuring χ_{cJ} suppression in finite nuclear matter[12], χ_{cJ} dissociation cross sections in the collision with a nucleon were calculated in the same potential model[13]. In the present work the nucleon-χ_{cJ} dissociation cross sections are applied to study χ_{cJ} suppression related to nucleon and antinucleon distributions in hadronic matter created in the central Pb + Pb and S + Pb collisions at the CERN-SPS energy. We first recapitulate the work of Ref.[13] in the next section. Then we discuss thermally averaged χ_{cJ} dissociation cross sections with the relative velocity of nucleon and χ_{cJ} in Section 3. χ_{cJ} survival probabilities reflecting the dissociations by protons, antiprotons, neutrons and antineutrons in hadronic matter produced in the central Pb + Pb and S + Pb collisions are calculated and plotted in Sections 4 and 5, respectively. Summary is given in the final section.

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2 χ_{cJ} dissociation cross sections by nucleon

The QCD-based potential used here was developed from the Buchmüller-Tye potential[11,14]. Wave functions of nucleons and charmed baryons involved in dissociation reactions result from a fit to mass splittings of baryons (charmed baryons) with spins $\frac{1}{2}$ and $\frac{3}{2}$. Since a charmonium is made of heavy quark and antiquark, some properties can be described in perturbative theory because of its large mass and small size. But it is not small enough to make nonperturbative effects totally negligible. Therefore, the production of charmonium can be understood within perturbative QCD, but its further interaction with surrounding matter is essentially soft in nature and cannot be treated perturbatively. An effective method to consider charmonium dissociation in a nonperturbative theory, which is strongly correlated with hadronic matter, is known as the quark exchange mechanism[10]. The reaction of a χ_{cJ} and a baryon ($c\bar{c} + q_1q_2q_3 \to q_1q_2c + q_3\bar{c}$) can be divided into six processes according to the colour interactions via one gluon propagation between (1) q_1 and c, (2) q_2 and c, (3) q_3 and c, (4) q_1 and $\bar{c}$, (5) q_2 and $\bar{c}$, (6) q_3 and $\bar{c}$. Accordingly, the Lorentz-invariant transition amplitude is

$$\mathscr{M} = \mathscr{N} \langle \Psi_{q_1q_2q_3} | \langle \Psi_{c\bar{c}} | (V_{q_1c} + V_{q_2c} + V_{q_3c} + V_{q_1\bar{c}} + V_{q_2\bar{c}} + V_{q_3\bar{c}}) | \Psi_{q_1q_2c} \rangle | \Psi_{q_3\bar{c}} \rangle, \tag{1}$$

where $\mathscr{N} = 4\sqrt{E_{q_1q_2q_3} E_{c\bar{c}} E_{q_3\bar{c}} E_{q_1q_2c}}$, Ψ is the wave function of a meson or a baryon, which is a product of space, colour, and spin-flavour wave functions, and V_{ab} ($a = q_1, q_2, q_3$; $b = c, \bar{c}$) is the QCD-based potential between quark (antiquark) a and quark (antiquark) b

$$V_{ab}(\boldsymbol{r}) = -\frac{\boldsymbol{\lambda}_a}{2} \cdot \frac{\boldsymbol{\lambda}_b}{2} \frac{3}{4} Kr - \frac{\boldsymbol{\lambda}_a}{2} \cdot \frac{\boldsymbol{\lambda}_b}{2} 16\pi^2 \int \frac{d^3\boldsymbol{Q}}{(2\pi)^3} \times \frac{\rho(\boldsymbol{Q}^2) - K/\boldsymbol{Q}^2}{\boldsymbol{Q}^2} \gamma_0^a \gamma_\mu^a \gamma^{0b} \gamma^{\mu b} e^{i\boldsymbol{Q}\cdot\boldsymbol{r}} \tag{2}$$

which depends on the relative coordinate $\boldsymbol{r}$ or particles a and b, a physical running coupling constant $\rho(\boldsymbol{Q}^2)$, the Dirac matrices γ^μ ($\mu = 0, 1, 2, 3$), the Gell-Mann matrices $\boldsymbol{\lambda}$, the gluon momentum $\boldsymbol{Q}$, and the string tension $K = 3/(16\pi^2\alpha')$ with the Regge slope $\alpha' = 1.04\,\mathrm{GeV}^{-2}$.

From the transition amplitude we get the total cross section

$$\sigma(s) = \frac{1}{32\pi s} \frac{|\boldsymbol{P}'(s)|}{|\boldsymbol{P}(s)|} \int_{-1}^{1} dz \, |\mathscr{M} \times (\boldsymbol{P}(s), \boldsymbol{P}'(s), z)|^2. \tag{3}$$

where $z = \cos\theta(\boldsymbol{P}, \boldsymbol{P}')$ and $\theta(\boldsymbol{P}, \boldsymbol{P}')$ is the angle between the momenta $\boldsymbol{P}$ and $\boldsymbol{P}'$ of incoming and outgoing particles in the center-of-mass frame of the χ_{cJ} and the proton.

We take χ_{c1} to illustrate the complex characters of the χ_{cJ} dissociation by a proton. Similar considerations are applied to the reactions of χ_{c0} and χ_{c2} with a proton or other baryons. Ref. [13] presents dissociation cross sections versus the center-of-mass energy $\sqrt{s}$ of the χ_{c1} and the proton in the nine channels

$$1: p + c\bar{c} \to \Lambda_c^+ + \bar{D}^0, S_{tot} = \frac{1}{2};$$

$$2: p + c\bar{c} \to \Lambda_c^+ + \bar{D}^{*0}, S_{tot} = \frac{1}{2};$$

$$3: p + c\bar{c} \to \Lambda_c^+ + \bar{D}^{*0}, S_{tot} = \frac{3}{2};$$

$$4: p + c\bar{c} \to \Sigma_c^{++} + D^-, S_{tot} = \frac{1}{2};$$

$$5: p + c\bar{c} \to \Sigma_c^{++} + D^{*-}, S_{tot} = \frac{1}{2};$$

$$6: p + c\bar{c} \to \Sigma_c^{++} + D^{*-}, S_{tot} = \frac{3}{2};$$

$$7: p + c\bar{c} \to \Sigma_c^{*++} + D^-, S_{tot} = \frac{3}{2};$$

$$8: p + c\bar{c} \to \Sigma_c^{*++} + D^{*-}, S_{tot} = \frac{1}{2};$$

$$9: p + c\bar{c} \to \Sigma_c^{*++} + D^{*-}, S_{tot} = \frac{3}{2}.$$

These processes of χ_{c1} absorbed by a proton involve both endothermic and exothermic reactions. For the endothermic reaction, taking $p + \chi_{c1} \to \Sigma_c^{++} + D^{*-}$ ($S_{tot} = 1/2$) as an example, the cross section starts from zero at the threshold energy, then enhances and reaches a peak value 14.3 mb at 4.6 GeV. For the exothermic reaction, taking $p + \chi_{c1} \to \Sigma_c^{++} + D^-$ ($S_{tot} = 1/2$) as an example, the cross section is infinite at the threshold energy and then declines rapidly. All of the absorption cross sections of the nine channels drop off exponentially towards higher center-of-mass energies. Therefore, a proton with the momentum which can provide energy $\sqrt{s}$ close to the threshold value has strong dissociation ability.

3 Thermal average

Now we consider the thermal average of the χ_{cJ} dissociation cross sections multiplied by the relative velocity v_{rel} of χ_{cJ}

and nucleon(antinucleon) while χ_{cJ} moves in hadronic matter produced in high-energy nucleus-nucleus collisions. Recognizing $f(\boldsymbol{r},\boldsymbol{P}_1,t)$ and $f(\boldsymbol{r},\boldsymbol{P}_2,t)$ as the phase-space distributions of proton and χ_{c1} with the momenta $\boldsymbol{P}_1$ and $\boldsymbol{P}_2$, respectively, we write the time evolution of χ_{c1} distribution as the following simple kinetic Boltzmann equation[15]:

$$\frac{\partial f(\boldsymbol{r},\boldsymbol{P}_2,t)}{\partial t}+\boldsymbol{V}\cdot\nabla f(\boldsymbol{r},\boldsymbol{P}_2,t)=$$
$$-f(\boldsymbol{r},\boldsymbol{P}_2,t)\int\frac{d^3\boldsymbol{P}_1}{(2\pi)^3}f(\boldsymbol{r},\boldsymbol{P}_1,t)\sigma_{abs}v_{rel},\tag{4}$$

where $\boldsymbol{V}$ is the velocity of χ_{c1} and σ_{abs} is the absorption cross section of χ_{c1} by a proton. Let $m_1(m_2)$ and $E_1(E_2)$ stand for the mass and energy of proton(χ_{c1}), respectively. The relative velocity is

$$v_{rel}=\frac{\sqrt{(p_1\cdot p_2)^2-m_1^2m_2^2}}{E_1E_2}.\tag{5}$$

Considering a thermal proton distribution as given by the Fermi-Dirac distribution

$$f_p(\boldsymbol{P}_1,t)=\frac{2}{\exp[E_1(\boldsymbol{P}_1)/T]+1}\tag{6}$$

which is independent of the coordinate $\boldsymbol{r}$ and gives the proton density

$$n_p(t)=\int\frac{d^3\boldsymbol{P}_1}{(2\pi)^3}f_p(\boldsymbol{P}_1,t),\tag{7}$$

we derive the thermally averaged dissociation cross section, which depends on the χ_{c1} momentum $\boldsymbol{P}_2$:

$$\langle\sigma_{abs}v_{rel}\rangle=\frac{1}{n_p(t)}\int\frac{d^3\boldsymbol{P}_1}{(2\pi)^3}f_p(\boldsymbol{P}_1,t)\sigma_{abs}[s(\boldsymbol{P}_1,\boldsymbol{P}_2)]v_{rel}.\tag{8}$$

Now we show our results of $\langle\sigma_{abs}v_{rel}\rangle$ against the transverse momentum of χ_{c1} at different temperatures in Fig.1 for the endothermal reaction $p+\chi_{c1}\rightarrow\Sigma_c^{++}+D^{*-}(S_{tot}=1/2)$ and in Fig.2 for the exothermal one $p+\chi_{c1}\rightarrow\Sigma_c^{++}+D^-(S_{tot}=1/2)$.

The quantity $\langle\sigma_{abs}v_{rel}\rangle$ can be regarded as the mean capability of protons to dissolve a χ_{c1} which is moving with the momentum $\boldsymbol{P}_2$ through a thermal proton matter in a channel. The higher χ_{c1} momentum we input, the lower thermally averaged dissociation cross section weighed with v_{rel} we get. And $\langle\sigma_{abs}v_{rel}\rangle$ always increases with the increasing temperature of the proton matter. We can understand these phenomena as follows: The higher χ_{c1} momentum offers larger center-of-mass energy $\sqrt{s}$, which gives smaller dissociation cross sections of both the endothermic and the exothermic reactions; Meanwhile, the exponential factor $e^{-E_1/T}$ has a stronger suppressing effect on the high proton momentum contribution to $\langle\sigma_{abs}v_{rel}\rangle$ and increases as T increases. The results show the approximate tendency of the dissociation capability with the variation of temperature. The thermal avergae governs the evolution of χ_{cJ} in proton matter.

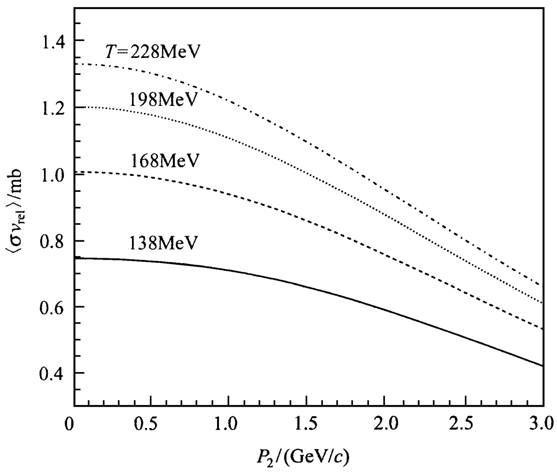

Fig.1. The thermally averaged cross sections of $p+\chi_{c1}\rightarrow\Sigma_c^{++}+D^{*-}(S_{tot}=1/2)$ for a χ_{c1} moving through proton matter with the momentum $\boldsymbol{P}_2$ at different temperatures T.

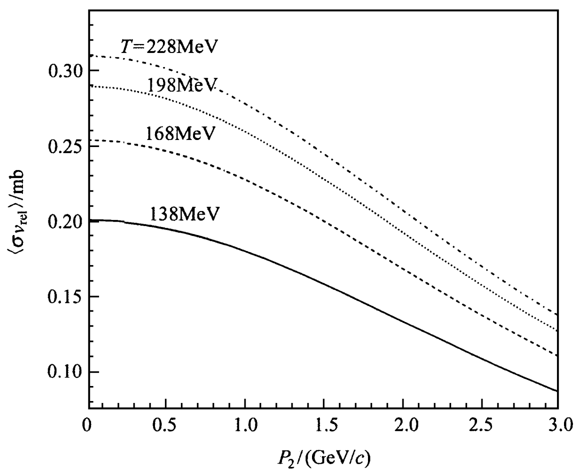

Fig.2. The thermally averaged cross sections of $p+\chi_{c1}\rightarrow\Sigma_c^{++}+D^-(S_{tot}=1/2)$ for a χ_{c1} moving through proton matter with the momentum $\boldsymbol{P}_2$ at different temperatures T.

4 Survival probability of χ_{cJ} in the central Pb + Pb collision

A χ_{cJ} meson is produced at the position $\boldsymbol{r}$ in the initial nucleus-nucleus collision. When the meson passes through hadronic matter, it is dissociated by the collisions with nucleons and antinucleons. We consider χ_{cJ} moving at the central rapidity. Then the survival probability of χ_{cJ} averaged over its initial position is

$$S(P_T) = \frac{\int d^2 r(R_A^2 - r^2)\exp[-\int_{\tau_f}^{\tau_{min}} d\tau(n_p(\tau) + n_{\bar{p}}(\tau)}{\int d^2 r(R_A^2 - r^2)} + \frac{n_n(\tau) + n_{\bar{n}}(\tau))\langle\sigma_{abs} v_{rel}\rangle]}{\int d^2 r(R_A^2 - r^2)}, \quad (9)$$

where R_A is the radius of the projectile nucleus and τ_{min} is the time when χ_{cJ} ceases to interact with hadronic matter. The cross section σ_{abs} is a sum of the nine channels of χ_{cJ} dissociations. n_p, $n_{\bar{p}}$, n_n and $n_{\bar{n}}$ denote the number densities of proton, antiproton, neutron and antineutron at a given time τ, respectively.

In Ref.[16], the anomalous J/Ψ suppression observed in Pb + Pb collisions at 158 GeV/c per nucleon was studied while property of hadronic matter was determined. The work presented a transverse velocity of hadronic matter $V_{ex\perp} = 0.75c$, a thermalization time $\tau_f = 2.9$fm/c at which the matter has the temperature $T_{therm} = 0.175$GeV, a freeze-out time $\tau_{fh} = 4.44$fm/c at which the freeze-out temperature is 0.139 GeV. We then use the velocity, these times and temperatures to calculate the survival probability of χ_{cJ} due to the collisions with protons, antiprotons, neutrons and antineutrons in hadronic matter. The number densities of proton (antiproton) are obtained from the total proton (antiproton) number N_p ($N_{\bar{p}}$) measured by NA49 collaboration[17] by

$$n_p = N_p/V(\tau), n_{\bar{p}} = N_{\bar{p}}/V(\tau), \quad (10)$$

where V is the volume of hadronic matter

$$V(\tau) = (2\tau + \frac{2R_A}{\gamma})\pi(R_A + \tau V_{ex\perp})^2. \quad (11)$$

The neutron (antineutron) number density is assumed to be equal to the proton (antiproton) number density. The dependence of survival probability of χ_{cJ} on transverse momentum is shown in Fig.3 for hadronic matter created in the central Pb + Pb collision at 158 GeV/c per nucleon.

5 Survival probability of χ_{cJ} in the central S + Pb collision

In a central S + Pb collision, less nucleons in the lead nucleus participate in the creation of hadronic matter since the sulphur nucleus has about half of the radius of the lead nucleus. The hadronic matter may not reach thermal equilibrium. No matter whether the hadronic matter is in thermal equilibrium or not, we can approximate each hadron distribution by a uniform distribution in space

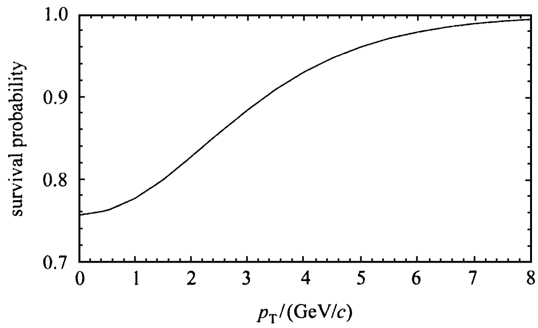

Fig.3. χ_{cJ} Survival probability in the central Pb + Pb collisions at 158 GeV/c per nucleon.

$$f = \frac{(2\pi)^2}{EVp_T}\frac{d^2N}{dp_T dy} = \frac{(2\pi)^2}{EVm_T}\frac{d^2N}{dm_T dy} \quad (12)$$

which gives hadron number density

$$n = \int \frac{d^3p}{(2\pi)^3} f. \quad (13)$$

Since each transverse mass spectrum of hadrons can be described by an inverse slope parameter T_{is}, we write

$$\frac{d^2N}{dm_T dy} = \frac{dN}{dy} C m_T^{\alpha} e^{-\frac{m_T}{T_{is}}}, \quad (14)$$

where the constant C is

$$C = \left[\int_m^{\sqrt{m^2+(\sqrt{s}/2)^2}} dm_T m_T^{\alpha} e^{-\frac{m_T}{T_{is}}}\right]^{-1}, \quad (15)$$

where $\sqrt{s}$ is the center-of-mass energy per colliding nucleon pair. The NA44 collaboration measured the proton and antiproton rapidity densities in sulphurlead collisions at the beam momentum 200 GeV/c per nucleon[18]. We approximate the rapidity densities by

$$\frac{dN}{dy} = \begin{cases} 12.8 & \text{if } |y| \leqslant 1 \\ 12.8e^{-(|y|-1)^2} & \text{if } |y| > 1 \end{cases}$$

for the proton and

$$\frac{dN}{dy} = \begin{cases} 0.95 & \text{if } |y| \leqslant 1 \\ 0.95e^{-(|y|-1)^2} & \text{if } |y| > 1 \end{cases}$$

for the antiproton. Due to the lack of neutron and antineutron rapidity densities, we assume that the neutron and proton have the same rapidity densities with their antiparticles, respectively. We keep the hadronic matter duration in the central S + Pb collision the same as that in the central Pb + Pb collision[16]. According to the measurement of NA44 collaboration[18], we set $\alpha = 1$ and the inverse slope of the m_T spectrum, $T_{is} = 0.221$ GeV for proton and neutron and 0.206 GeV for antiproton and antineutron, respectively. Since the sulphur nucleus has the radius $R_S = 3.62$ fm smaller than the lead nucleus $R_{Pb} = 6.74$fm, the volume of hadronic matter formed in the central S + Pb collision is

$$V(\tau) = \left(2\tau + \frac{2R_{Pb}}{\gamma}\right)\pi(R_S + \tau V_{ex\perp})^2. \qquad (16)$$

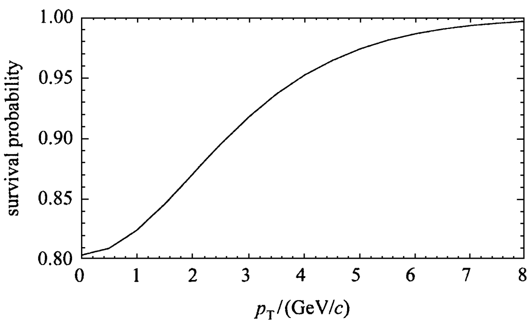

Fig.4. χ_{cJ} survival probability in the central S + Pb collisions at 200 GeV/c per nucleon.

The χ_{cJ} survival probability involving only the dissociations by nucleons and antinucleons in hadronic matter is calculated with Eq.(9) and plotted in Fig.4. It is visible that the survival probability in the central S + Pb collision is larger than the survival probability in the central Pb + Pb collision. This difference is caused by the hadronic matter initially formed, which has the transverse size of about twice the small radius of sulphur nucleus.

6 Summary

We have calculated the thermal average $\langle \sigma_{abs} v_{rel} \rangle$ which affects the χ_{cJ} evolution and suppression in hadronic matter. The average decreases with χ_{cJ} momentum increasing at a fixed temperature and increases with temperature increasing at a fixed χ_{cJ} momentum. Nucleon- χ_{cJ} dissociation cross sections have been applied to study χ_{cJ} suppression in hadronic matter created in the central Pb + Pb and S + Pb collisions at the CERN-SPS energy. The survival probability of χ_{cJ} determined by the collisions from nucleons and antinucleons increases with the χ_{cJ} transverse momentum increasing. The suppression is not strong but not negligible at low p_T. The χ_{cJ} collisions with baryons and antibaryons may give appreciable contribution to the total χ_{cJ} suppression in hadronic matter.

References

1 An T, Qin C W, Xia Y X. hep-ph/9701207
2 Ftacnik J, Lichard P, Pisut J. Phys. Lett., 1988, **B 207**: 194; Gavin S, Gyulassy M, Jackson A. Phys. Lett., 1988, **B 207**: 257; Vogt R et al. Phys. Lett., 1988, **B207**: 263
3 Shuryak E V. Sov. J. Nucl. Phys., 1978, **28**: 408
4 Ramello L(NA50 Collaboration). Nucl. Phys., 2003, **A715**: 243c
5 Blaizot J P, Ollitrault J Y. Nucl. Phys., 1996, **A610**: 452c; Phys. Rev Lett., 1996, **77**: 1703
6 Kharzeev D. Nucl. Phys., 1996, **A610**: 418c
7 Wong C Y. Nucl. Phys., 1996, **A610**: 434c; Phys. Rev., 1997, **C55**: 2621
8 Matsui T, Satz H. Phys. Lett., 1986, **B178**: 416
9 Schuler G A. CERN-TH/94-7170
10 Barnes T, Swanson E S. Phys. Rev., 1992, **D46**: 131; Martins K, Blaschke D, Quack E. Phys. Rev., 1995, **C51**: 2723
11 Xu X M. Nucl. Phys., 2002, **A697**: 825
12 Zoccoli A(the HERA-B Collaboration). Nucl. Phys., 2003, **A715**: 280c
13 Feng Y C, Xu X M, Zhou D C. Chin. Phys. Lett., 2002, **19**: 1602
14 Buchmüller W, Tye S H H. Phys. Rev., 1981, **D24**: 132
15 Blaizot J P, Ollitrault J Y. Phys. Rev., 1989, **D39**: 232
16 Xu X M, Wong C Y, Barnes T. Phys. Rev., 2003, **C67**: 014907
17 Siklér F(the NA49 Collaboration). Nucl. Phys., 1999, **A661**: 45c
18 Bearden I G et al. Phys. Rev., 1998, **C57**: 837

核子诱导的 χ_{cJ} 抑制*

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摘要 本文主要运用夸克交换模型计算所得的核子— χ_{cJ} 离解截面研究 Pb + Pb 和 S + Pb 中心碰撞过程中强子物质中的 χ_{cJ} 抑制.并定性地研究了核子动量和核子气温度对热平均截面地影响.Pb + Pb 和 S + Pb 中心碰撞中 χ_{cJ} 存活率表明核子与反核子所诱导的 χ_{cJ} 抑制是很明显的.

关键词 离解截面 热平均截面 压低

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