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Υ production as a probe for early state dynamics in high energy nuclear collisions at RHIC

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ABSTRACT

Υ production in heavy ion collisions at RHIC energy is investigated. While the transverse momentum spectra of the ground state $\Upsilon(1s)$ are controlled by the initial state Cronin effect, the excited $b\bar{b}$ states are characterized by the competition between the cold and hot nuclear matter effects and sensitive to the dissociation temperatures determined by the heavy quark potential. We emphasize that it is necessary to measure the excited heavy quark states in order to extract the early stage information in high energy nuclear collisions at RHIC.

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Quarkonium production in relativistic heavy ion collisions is widely accepted as a probe of deconfinement phase transition at finite temperature and density. The J/ψ suppression [1] has been observed at SPS [2,3] and RHIC [4] energies and considered as a signature of the created new state of matter, the so-called quark–gluon plasma (QGP). At RHIC energy, however, the J/ψ production and suppression mechanisms are complicated, there are primordial production and nuclear absorption in the initial state and regeneration [5–8] and anomalous suppression during the evolution of the hot medium.

Υ mesons, the bound states of bottom quarks, may offer a relatively cleaner probe into the hot and dense medium [9–11]. At RHIC energy, there are three important advantages in studying Υ production compared with J/ψ : (i) Υ regeneration in the hot medium can be safely neglected [12] due to the small production cross section of bottom quarks in nucleon + nucleon collisions. The initial creation becomes the only production mechanism and the perturbative QCD calculations are more reliable for estimating the production. (ii) Υ s are so heavy, there is almost no feed-down for them. (iii) From the Υ measurement in d + Au collisions where there is no hot nuclear matter effect, the nuclear modification factor is about unity, implying that the cold nuclear absorption is negligible [13]. Therefore, the heavy and tightly bound Υ s can only be dissociated in the QGP phase. It is interesting to note that the recent experimental result in Au + Au collisions at RHIC

[14] has already indicated a strong medium effect on Υ production.

The quarkonium dissociation temperature in the hot medium can be determined by solving the Schrödinger equation for $c\bar{c}$ or $b\bar{b}$ system with potential V between the two heavy quarks [15]. The potential depends on the dissociation process in the medium. For a rapid dissociation where there is no heat exchange between the heavy quarks and the medium, the potential is just the internal energy U , while for a slow dissociation, there is enough time for the heavy quarks to exchange heat with the medium, and the free energy F which can be extracted from the lattice calculations is taken as the potential [16,17]. From the thermodynamic relation $F = U - TS < U$ where S is the entropy density, the surviving probability of quarkonium states with potential $V = U$ is larger than that with $V = F$. In the literatures, a number of effective potentials in between F and U have been used to evaluate the charmonium evolution in QCD medium [15,17,18].

In this Letter we investigate Υ mid-rapidity production at RHIC energy ($\sqrt{s_{NN}} = 200$ GeV), by solving a classical Boltzmann equation for the phase space distribution of Υ states moving in a hydrodynamic background medium. Since the Υ transverse momentum distribution should be more sensitive to the dynamic evolution of the system, compared with the global Υ yield, we will calculate not only the centrality dependence of the nuclear modification factor, but also its transverse momentum dependence and the averaged transverse momentum for the ground and excited Υ states. We will also discuss the dependence of these observables on the heavy quark potential and the similarity between Υ production at RHIC and J/ψ production at SPS.

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From the experimental data in $p + p$ collisions, 51% of the observed ground state $\Upsilon(1s)$ is from the direct production, and the decay contributions from the excited $b\bar{b}$ states $\Upsilon(1p)$, $\Upsilon(2s)$, $\Upsilon(2p)$ and $\Upsilon(3s)$ are respectively 27%, 11%, 10% and 1% [19]. The other two states $\eta_b(1s)$ and $\eta_b(2s)$ are scalar mesons with typical width of strong interaction and therefore not considered here. To simplify the numerical calculation, we will not distinguish $\Upsilon(2p)$ from $\Upsilon(1p)$ and $\Upsilon(3s)$ from $\Upsilon(2s)$ and take the contribution fractions from the directly produced $\Upsilon(1s)$, $\Upsilon(1p)$ and $\Upsilon(2s)$ to the observed $\Upsilon(1s)$ in the final state to be $a_\Upsilon = 51\%$, 37% and 12% .

Like the description for J/ψ [20], the Υ motion in a hot medium is characterized by the classical transport equation

$$p^\mu \partial_\mu f_\Upsilon = -C f_\Upsilon, \quad (1)$$

where $f_\Upsilon(\vec{p}, \vec{x}, t)$ is the Υ distribution function in the phase space with $\Upsilon = 1s, 1p, 2s$, and the loss term C is responsible to Υ suppression in the hot medium. We have neglected here the Υ regeneration at RHIC energy, as discussed above. Taking into account the gluon dissociation process $\Upsilon + g \rightarrow b + \bar{b}$ as the suppression source, the loss term can be written as

$$C = \int \frac{d^3\vec{k}}{(2\pi)^3 E_g} F(k, p) f_g(k, T, u) \sigma(k, p, T), \quad (2)$$

where \vec{k} is the gluon momentum, $E_g = |\vec{k}|$ the gluon energy, $F(k, p) = k_\mu p^\mu$ the flux factor, $f_g(k, T, u)$ the gluon thermal distribution as a function of the local temperature T and velocity u_μ of the medium, and $\sigma(k, p, T)$ the dissociation cross section at finite temperature. The cross section in vacuum can be calculated with the Operator Production Expansion method [21–24] and is often used for J/ψ suppression and should be better for Υ suppression. The medium effect on the cross section is reflected in the temperature dependence of the Υ binding energy ϵ_Υ . By solving the Schrödinger equation for the $b\bar{b}$ system with the heavy quark potential V at finite temperature, one obtains $\epsilon_\Upsilon(T)$ and the wave function $\psi(\vec{x}, T)$ and in turn the average size of the system $\langle r \rangle(T)$. With increasing T , ϵ_Υ decreases and vanishes at the dissociation temperature T_Υ and $\langle r \rangle$ increases and goes to infinity at T_Υ . From the lattice simulation [25] on the J/ψ spectral function at finite temperature, the shape of the spectral function changes only a little for $T < T_{J/\psi}$ but suddenly collapses around the dissociation temperature $T_{J/\psi}$. To simplify our numerical calculation, we replace the temperature dependence of the binding energy in the cross section by a step function, $\sigma(k, p, T) = \sigma(k, p) / \Theta(T_\Upsilon - T)$. Under this approximation, while the cross section becomes temperature independent at $T < T_\Upsilon$, the dissociation rate $\alpha = C / \epsilon_\Upsilon$ depends still on the hot medium, since the gluon density is sensitive to the temperature.

For $V = U$, H. Satz and his collaborators [15,26] solved the Schrödinger equation and found the dissociation temperatures $T_\Upsilon / T_c = 4, 1.8, 1.6$ for $\Upsilon = 1s, 1p, 2s$, respectively, where $T_c = 165$ MeV [27] is the critical temperature for the deconfinement. Since the lattice calculated potential is mainly in the temperature region $T / T_c < 4$, $T_\Upsilon / T_c = 4$ is considered as a low limit of the dissociation temperature for the ground state. In the same way, we numerically solved the Schrödinger equation for $V = F$ and the dissociation temperatures $T_\Upsilon / T_c = 3, 1.1, 1$ for $\Upsilon = 1s, 1p, 2s$, respectively. For all Υ states, the dissociation temperatures are about 30% lower in case of $V = F$ compared to that of $V = U$. In Fig. 1, we show the Υ dissociation rate α as a function of transverse momentum at fixed temperature $T_c < T < T_\Upsilon$ in the case of $V = U$. In the calculation here we have chosen a typical medium velocity $v_{QGP} = 0.5$ and assumed that \vec{v}_{QGP} and Υ momentum \vec{p} have the same direction. All the rates are large at low momentum and drop off at high momentum. When the temperature increases from

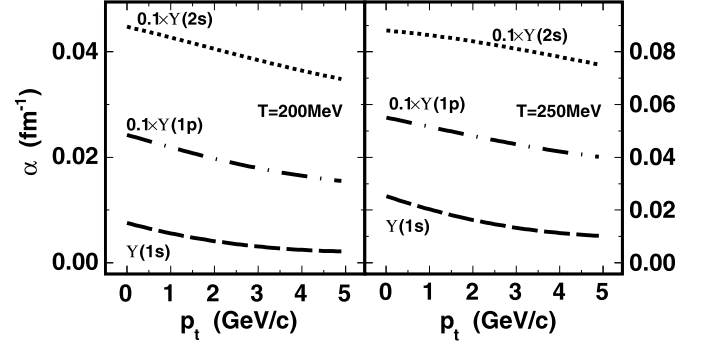


Fig. 1. The Υ dissociation rate α as a function of transverse momentum at temperature $T = 200$ MeV (left panel) and 250 MeV (right panel) for the potential $V = U$. The medium velocity is fixed as $v_{QGP} = 0.5$ and its direction is chosen as the same as the Υ momentum. $\Upsilon(1s)$, $\Upsilon(1p)$ and $\Upsilon(2s)$ are respectively shown by dashed, dot-dashed and dotted lines. The rates for $\Upsilon(1p)$ and $\Upsilon(2s)$ are multiplied by a factor 0.1.

200 MeV (left panel) to 250 MeV (right panel), the rates for all Υ states increase by a factor of about 2. This can be understood qualitatively by the temperature dependence of the gluon density, $n_g(T = 250 \text{ MeV}) / n_g(T = 200 \text{ MeV}) = (250/200)^3 = 1.95$.

In our following numerical calculations, the local temperature $T(\vec{x}, t)$ and medium velocity $u_\mu(\vec{x}, t)$ which appear in the gluon distribution function $f_g(k, T, u)$ and step function $\Theta(T_\Upsilon - T)$ are controlled by the ideal hydrodynamic equations

$$\partial_\mu T^{\mu\nu} = 0, \quad \partial_\mu (n_B u^\mu) = 0, \quad (3)$$

where $T^{\mu\nu}$ is the energy–momentum tensor, and n_B the baryon density. Taking into account the Hubble-like expansion assumption for the longitudinal motion [28], the above hydrodynamics describes the transverse evolution of the medium in the central rapidity region. To close the hydrodynamic equations, we take the equation of state [27,29] for ideal parton gas with parton masses $m_u = m_d = m_g = 0$ and $m_s = 150$ MeV and hadron gas with hadron masses up to 2 GeV. Here we did not consider the back-coupling of the Υ states to the medium evolution. The initial condition for the hydrodynamic equations is determined by the corresponding nucleon + nucleon collisions and colliding nuclear geometry [30], leading to an initial temperature $T_i = 340$ MeV.

The transport equation (1) can be solved analytically [30]. The initial transverse momentum distribution f_Υ can be described by the Monte Carlo event generator PYTHIA with MSEL = 62 [31] for the nucleon + nucleon collisions and the Glauber model for the nuclear geometry. Since the collision time for the two nuclei to pass through each other at RHIC energy is less than the starting time of the hot medium, all the cold nuclear matter effects can be included in the initial distribution. Considering the fact that there is almost no Υ suppression in $d + \text{Au}$ collisions [13], we neglect the nuclear absorption and take into account only the Cronin effect [32,33], namely the gluon multi-scattering with nucleons before the two gluons fuse into an Υ . The Cronin effect leads to a transverse momentum broadening, the averaged transverse momentum square $\langle p_t^2 \rangle_{NN}$ in nucleon + nucleon collisions is extended to $\langle p_t^2 \rangle_{NN} + a_{gN} l$, where l is the path length that the two gluons travel in the cold nuclear medium and a_{gN} is a constant determined by the $p + A$ data.

With the known distribution function $f_\Upsilon(\vec{p}, \vec{x}, t)$, we can calculate the yield N_{AA}^Υ in the final state by integrating f_Υ over the hypersurface in the phase space determined by the critical temperature T_c . The nuclear modification factors defined by $R_{AA} = N_{AA}^\Upsilon / (N_{coll} N_{NN}^\Upsilon)$ are shown in Fig. 2 as functions of the number of participant nucleons N_{part} in $\text{Au} + \text{Au}$ collisions at $\sqrt{s} = 200$ A GeV,

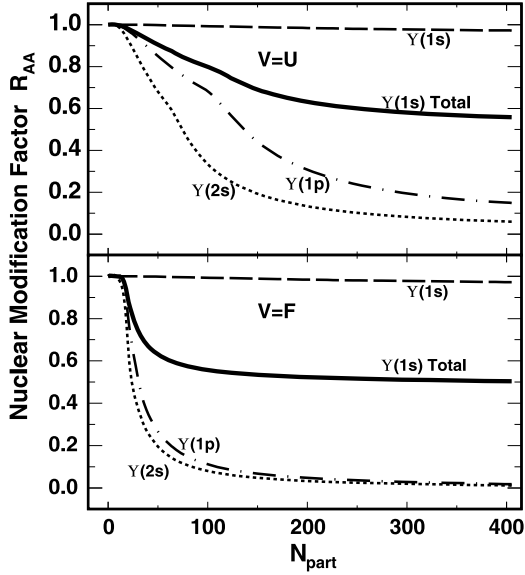


Fig. 2. Centrality dependence of the nuclear modification factors R_{AA} in Au + Au collisions at top RHIC energy $\sqrt{s_{NN}} = 200$ GeV. Upper and lower panels are for the heavy quark potentials $V = U$ and $V = F$, respectively. The directly produced $\Upsilon(1s)$, $\Upsilon(1p)$, $\Upsilon(2s)$ and the total $\Upsilon(1s)$ are respectively shown by dashed, dot-dashed, dotted and solid lines.

where N_{coll} is the number of binary collisions and N_{NN}^{Υ} is the Υ yield in the corresponding nucleon + nucleon collisions. Since the heavy quark potential at finite temperature is not yet clear, we take the two limits of $V = U$ and $V = F$ to determine the Υ dissociation temperature T_{Υ} . For the ground state $\Upsilon(1s)$, the binding energy is about 1.1 GeV which is much larger than the typical temperature of the fireball $T \sim 300$ MeV at RHIC energy. Therefore, $\Upsilon(1s)$ is unlikely to be destroyed in heavy ion collision at RHIC. Considering the fact that the dissociation temperatures $T_{\Upsilon} = 4T_c$ for $V = U$ and $3T_c$ for $V = F$ are both far above the temperature of the fireball, the suppression due to the gluon dissociation is very small and independent of the heavy quark potential. As to the excited states, the situation is different as their binding energies are much smaller and thus their yields are strongly suppressed. Especially, at $V = F$ which leads to the lowest dissociation temperatures around the phase transition for $\Upsilon(1p)$ and $\Upsilon(2s)$, almost all of them are eaten up by the fireball in semi-central and central collisions. Including the decay contribution from the excited states to the ground state, the finally observed nuclear modification factor for $\Upsilon(1s)$, $R_{AA} = \sum_{\Upsilon=1s,1p,2s} a_{\Upsilon} N_{AA}^{\Upsilon} / (N_{coll} N_{NN}^{\Upsilon})$ is controlled by both the ground and excited states. In central Au + Au collisions, as one can see in the figure, $R_{AA} \sim a_{1s} = 0.51$. Integrating over the number of participant nucleons, the R_{AA} in minimum bias events is 0.53 for $V = F$ and 0.63 for $V = U$. Both values are in reasonable agreement with the preliminary PHENIX data $R_{AA} < 0.64$ [14]. As one can see in the figure, while the overall R_{AA} shows limited sensitivity to the heavy quark potential, the excited states display different dependence on the potential used in the calculation.

In our numerical calculations, the momentum parameters $\langle p_t^2 \rangle_{NN}$ and a_{gN} are respectively taken to be 7.1 (GeV/c)² from the PYTHIA simulation [31] and 0.2 (GeV/c)²/fm to best describe the available data for p + A collisions [34]. In order to further address the Υ production dynamics, we calculated the nuclear modification factor R_{AA} as a function of transverse momentum p_t in central Au + Au collisions at RHIC energy, see Fig. 3. There are three nuclear matter effects that may affect the Υ p_t dependence: the Cronin effect in the initial state, the leakage effect [1,30] for higher p_t particles, and the suppression mechanism in the hot

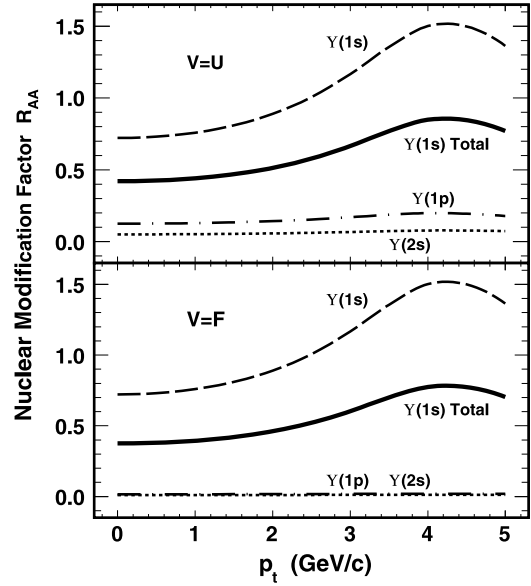


Fig. 3. Transverse momentum dependence of the nuclear modification factors R_{AA} in central Au + Au collisions at top RHIC energy $\sqrt{s_{NN}} = 200$ GeV. The peak caused by the Cronin effect is clear at $p_t \sim 4.5$ GeV/c for both potentials.

medium. While both the Cronin effect and leakage effect lead to a p_t broadening, i.e. reduction of low p_t particles and enhancement of high p_t particles, a strong enough suppression may weaken the broadening. The reason is the following: When the gluon traveling length l which characterizes the Cronin effect is long, the temperature which controls the suppression becomes high, the competition between the Cronin effect and the suppression may reduce the p_t broadening. For the ground state, there is only a weak suppression, a very strong p_t broadening due to the Cronin effect and leakage effect is expected. Since most of the excited states are dissociated in central collisions at both $V = U$ and $V = F$, their p_t broadening is strongly suppressed and not sensitive to the heavy quark potential. The shape of the finally observed total R_{AA} is determined by the directly produced $\Upsilon(1s)$, as shown in Fig. 3.

To obtain more dynamic information on the nuclear medium through survived excited states, we calculated the averaged transverse momentum square $\langle p_t^2 \rangle_{AA}$ as a function of centrality for Au + Au collisions, the results are shown in Fig. 4. To reduce the theoretical uncertainty in $\langle p_t^2 \rangle_{NN}$ and focus on the nuclear matter effect, we considered the difference between nucleus + nucleus and nucleon + nucleon collisions, $\Delta \langle p_t^2 \rangle \equiv \langle p_t^2 \rangle_{AA} - \langle p_t^2 \rangle_{NN}$. For the directly produced ground state $\Upsilon(1s)$, the suppression is weak and the Cronin effect plays the dominant role. As a result, $\Delta \langle p_t^2 \rangle$ increases monotonously with collision centrality. For the excited states, however, the effect of initial Cronin effect is overwhelmed by the disassociation especially in central collisions. In other words, in the most central collisions, the high temperature region is larger than that in peripheral collisions, most of the excited Υ s are destroyed. Therefore, as one can see, the value of $\Delta \langle p_t^2 \rangle$ goes up in peripheral collisions due to the Cronin effect, then becomes saturated in semi-central collisions from the competition between the Cronin effect and the increased suppression, and finally starts to decrease when the suppression becomes strong. In addition, as one can see in the figure, in case of $V = F$, the decrease is remarkable due to the stronger suppression effect. Different from the total $R_{AA}(N_{part})$ and $R_{AA}(p_t)$ which are approximately one half of the corresponding values for the directly produced $\Upsilon(1s)$, see Figs. 2 and 3, the total $\Delta \langle p_t^2 \rangle$ is very close to the one for the ground state, as shown in Fig. 4.

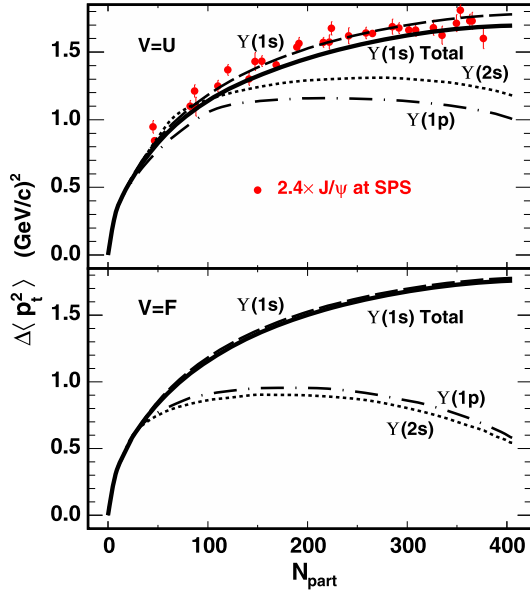


Fig. 4. Centrality dependence of the difference $\Delta\langle p_t^2 \rangle \equiv \langle p_t^2 \rangle_{AA} - \langle p_t^2 \rangle_{NN}$ between the averaged transverse momentum square from Au + Au and p + p collisions at top RHIC energy $\sqrt{s_{NN}} = 200$ GeV. For comparison, we showed in the upper panel also the J/ψ data at SPS energy [2] multiplied by a factor 2.4.

It is interesting to compare the Υ production at RHIC energy and the J/ψ production at SPS energy. Assuming there is no Υ regeneration at RHIC and no J/ψ regeneration at SPS, the production mechanism in the two cases is then characterized by the initial creation. In addition, from the relationship between the fireball temperature and the dissociation temperature for the ground state at $V = U$, $T_\Upsilon = 4T_c \gg T_{RHIC}$ and $T_{J/\psi} = 2T_c \gg T_{SPS}$, the suppression of $\Upsilon(1s)$ at RHIC and J/ψ at SPS is negligible. Therefore, the averaged transverse momentum squares for Υ in Au + Au collisions at RHIC and J/ψ in Pb + Pb collisions at SPS are related to each other through the Cronin effect,

$$\Delta\langle p_t^2 \rangle_{\Upsilon}^{RHIC} = \frac{a_{gN}^{RHIC} R_{Au}}{a_{gN}^{SPS} R_{Pb}} \Delta\langle p_t^2 \rangle_{J/\psi}^{SPS} = 2.4 \Delta\langle p_t^2 \rangle_{J/\psi}^{SPS}, \quad (4)$$

where we have taken $a_{gN}^{SPS} = 0.08$ GeV²/fm [32,33], and R_{Au} and R_{Pb} are the nuclear radii. This relation in fact predicts that the centrality dependence of $\Delta\langle p_t^2 \rangle$ for Υ at RHIC is proportional to that for J/ψ at SPS. In the upper panel of Fig. 4 we showed the J/ψ data at SPS [2] multiplied by the factor 2.4. It is clear that the relation (4) works well. For $R_{AA}(N_{part})$ and $R_{AA}(p_t)$, their behavior depends on the details of the hot medium, it becomes difficult to obtain similar relations between Υ at RHIC and J/ψ at SPS.

How hot is the fireball formed in relativistic heavy ion collisions? This is a crucial question that will have an influence on all signatures for QGP formation. In all above calculations, the initial temperature $T_i = 340$ MeV is determined by the initial energy density and baryon density which are controlled by the nucleon + nucleon collisions and the nuclear geometry. To extract the initial temperature of the system from Υ production, we now take T_i as a free parameter and calculate the momentum integrated R_{AA} as a function of T_i in central Au + Au collisions at RHIC energy, the result is shown in Fig. 5. While in case of $V = F$, see bottom plot of Fig. 5, the values of R_{AA} are almost constants in the temperature region $1.5 < T_i/T_c < 2$ which is the expected initial temperature region for collisions at RHIC, for $V = U$, see top plot of Fig. 5, the excited states and the finally observed ground state are sensitive to the temperature. Therefore, the experimental

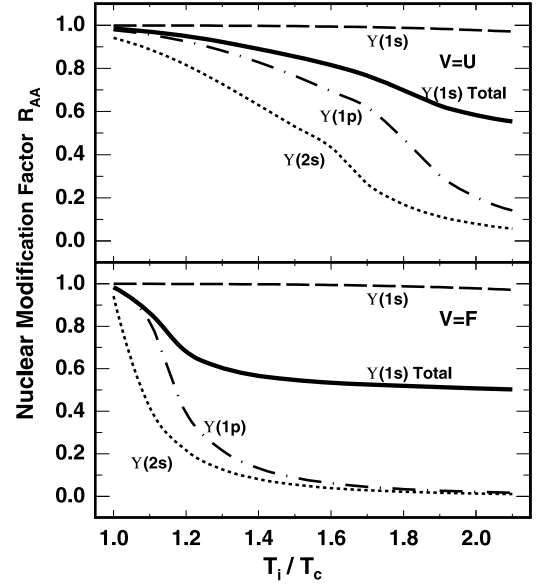


Fig. 5. Initial temperature dependence of the nuclear modification factor R_{AA} in central Au + Au collisions at top RHIC energy $\sqrt{s_{NN}} = 200$ GeV.

results of R_{AA} for any state will allow us to extract the information on the initial temperature of the system.

In summary, we studied Υ production in high energy nuclear collisions at RHIC in a transport model. The observed $\Upsilon(1s)$ is mainly from the direct production, and the contribution from the feed down of the excited states is small. The transverse momentum distribution of $\Upsilon(1s)$ is not sensitive to the hot medium, but characterized by the Cronin effect in the initial stage. The above conclusion is almost independent of the heavy quark potential. However, the behavior of the excited Υ states is controlled by the competition between the cold and hot nuclear matter effects and sensitive to the heavy quark potential. Therefore, the yield and transverse momentum distribution for the excited states should be measured in the future experiments, in order to probe the dynamic properties of the formed fireball. The initial state Cronin effect can be studied via the centrality dependence of $\langle p_t^2 \rangle$ in A + A collisions. We did not address the influence of the parton distribution in A + A collisions [35,36]. Although it will affect the details of the predictions made in this Letter, the qualitative trends, especially the nature of the high sensitivity of the excited Υ states to the potential and initial temperature, will remain to be true. The consideration on the velocity dependence of the dissociation temperature and the influence of reduced binding energy in low temperature region will be discussed in the future.

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