J/ψ production from charm coalescence in relativistic heavy ion collisions

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Abstract

J/ψ production and collective flow is studied with a coalescence model based on phase space distribution of charm quarks from a multi-phase transport model simulation of relativistic heavy ion collisions. Both the yield and the flow of J/ψ particles are sensitive to charm quark final state interactions. As the charm quark rescattering cross section increases from 3 mb to 10 mb, J/ψ elliptic flow increases faster than corresponding light hadron elliptic flows. The $v_2(p_t)$ of J/ψ crosses that of D mesons to reach a value that is about the peak value of the D meson flow but at a higher $p_t$. As J/ψ elliptic flow has only contributions from charm quarks, it complements D meson elliptic flow in reflecting charm properties in the Quark-Gluon Plasma.

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Experimental data from the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab (BNL) revealed fascinating properties of the Quark-Gluon Plasma (QGP) produced in relativistic nucleus-nucleus collisions \[1, 2, 3, 4, 5, 6\]. The $J/\psi$ particle is one of the important probes of QGP properties. It was proposed as a signature of QGP formation because of its dissociation due to color screening inside the Quark-Gluon Plasma \[7\]. Dissociations due to comover scatterings have also been studied to interpret experimental data at SPS energies \[8, 9, 10\]. Recently, lattice Quantum Chromodynamics (QCD) calculations show that the $J/\psi$ particle can survive the plasma up to about $2T_c$ \[11, 12\]. The survival of $J/\psi$ was also shown by potential models \[13\]. This leads to new insights into the experimental data \[14\]. At RHIC energies, many pairs of charm and anti-charm quarks can be produced in a single event. These charm and anti-charm quarks may recombine into $J/\psi$ particles. The recombination can contribute significantly to the final $J/\psi$ yield \[15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25\]. In this paper, $J/\psi$ production and flow will be studied by a phase-space coalescence model using the charm freeze-out information from a multi-phase transport (AMPT) model. In the following, the AMPT model and the coalescence formalism will be reviewed. This is followed by the presentation of results including the $J/\psi$ yield, $\langle p_t^2 \rangle$, $p_t$ distributions, and $v_2(p_t)$. Finally, a summary will be given with the implications of these results on the QGP dynamics.

The $J/\psi$ production in this study is based on the freeze-out phase space information of charm quarks from the AMPT model. The AMPT model is a transport model that simulates relativistic heavy ion collisions \[26, 27, 28, 29\]. It uses the HIJING model \[30\] to provide initial conditions. Either mini-jet partons, or partons from string melting will participate in the space-time evolution of the system. The parton evolution is carried out by the ZPC parton cascade model \[31\]. At parton freeze-out, partons are converted into hadrons using either the Lund string fragmentation model or a coordinate-space coalescence model that combines nearest partons into hadrons. Then the ART hadronic transport model \[32, 33\] is used to evolve the hadronic system. The AMPT model can reasonably describe particle distributions at RHIC. It is also successful in showing the importance of partonic evolution on elliptic flow and HBT radii \[34, 35, 36\]. In Ref. \[37\], charm flow in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is studied using the AMPT model in the string melting scenario with the perturbative method. The initial $D$ mesons follow a parametrization of $D$ meson $p_t$ distributions from the STAR collaboration \[38\] and a rapidity plateau between -2 and +2.
They are dissociated into charm quarks. Screened Coulomb cross sections are used for the rescatterings. Results from the 3mb cross section case are compared to those using a 10mb cross section. The D meson elliptic flow and non-photonic electron elliptic flow are found to be very sensitive to the charm rescattering cross sections.

In the following, the charm quark freeze-out information will be used for the study of production of the \(J/\psi\) particle using a phase-space coalescence model \[39, 40, 41, 42\]. In this model, the \(J/\psi\) momentum distribution is given by

\[
\frac{d^3 N_{J/\psi}}{d^3 p} = g_{J/\psi} \int \frac{d^3 q \, d^3 R \, d^3 r}{(2\pi)^{3x2}} f_c(\vec{x}_1, \vec{p}_1) f_c(\vec{x}_2, \vec{p}_2) f_W^{J/\psi}(\vec{r}, \vec{q}) .
\]

In the above formula, \(g_{J/\psi} = 1/12\) is the degeneracy factor of \(J/\psi\) production from charm and anti-charm quarks. \(\vec{q}\) is the relative momentum, \(\vec{r}\) is the relative position, and \(\vec{R}\) is the center-of-mass position of a pair. \(f_c, f_{\bar{c}}\) are the freeze-out phase-space distributions of charm and anti-charm quarks. \(f_W^{J/\psi}\) is the \(J/\psi\) Wigner function. With a Gaussian spatial wave function,

\[
f_W^{J/\psi}(\vec{r}, \vec{q}) = 8 \exp \left( -\frac{r^2}{\sigma^2} - \frac{q^2}{\sigma^2} \right).
\]

The width \(\sigma\) is related to the \(J/\psi\) rms radius by \(r_{\text{rms}}^2 = \frac{3}{8}\sigma^2\). \(r_{\text{rms}}\) is taken to be 0.5 fm as given by the potential model \[43\]. \(J/\psi\) production from two freeze-out distributions will be compared. One has 3mb parton rescattering cross sections, and the other has 10mb cross sections. Only \(J/\psi\) production from coalescence is taken into account. There is no production and survival from initial nucleon-nucleon collisions. The above coalescence approach cannot accurately account for binding energy. No feeddowns from higher charmonium resonances are taken into account.

The \(J/\psi\) rapidity density per binary nucleon-nucleon collision as a function of the number of participant nucleons is shown in Fig. \[\] As expected, the \(J/\psi\) yield increases with the number of participants. The 3mb case has a larger yield compared to the 10mb case. In central collisions, it can be larger by a factor of about 2.4. This is because of charm and anti-charm quarks are closer in phase-space with smaller cross section and less rescatterings. The solid curves are for the case with 1.4mb for the charm production cross section in nucleon-nucleon collisions \[44\]. At the moment, the charm production cross section has large uncertainty. When the cross section goes down to 0.6mb \[45\], the \(J/\psi\) yield decreases to about 20% of the 1.4 mb result. For central collisions, both the 3mb case and the 10mb case can give suppression consistent with preliminary PHENIX data \[46\] relative to the
production in $p + p$ collisions [47]. It is also interesting to see that the centrality dependence has almost the same shape as the production from recombination, e.g., from Grandchamp and Rapp’s calculations [21]. In other words, coalescence and recombination are closely related to each other. If the survival of charmonium from initial nucleon-nucleon collisions is taken into account, the $J/\psi$ results are expected to be similar to those of Grandchamp and Rapp.

![FIG. 1: $J/\psi$ yield per binary nucleon-nucleon collision as a function of the number of participant nucleons. The data point is from Ref. [47].](image)

The averaged $p_t^2$ as a function of the number of participants is shown in Fig. 2. The 10 mb case has more radial flow and is above the 3 mb case. The $\langle p_t^2 \rangle$ increases with centrality as more radial flow is generated in the 10 mb case. The 3 mb case is slightly different. A closer look at the $p_t$ distributions reveals that in peripheral collisions, high $p_t$ charm quarks escape easily and are not affected, while in central collisions, the quenching of high $p_t$ charm leads to a decrease of $\langle p_t^2 \rangle$ of $J/\psi$ particles. The $\langle p_t^2 \rangle$ is about 3 GeV$^2$ in the 10 mb case and is about 1.5 GeV$^2$ in the 3 mb. The 10 mb case is comparable to recent calculations.
from recombinations by Thews et al. [16, 48] and also comparable to preliminary PHENIX central electron arm data [46].

Fig. 2: Averaged $p_t^2$ at mid-rapidity as a function of the number of participant nucleons.

Fig. 3 shows the elliptic flow parameter $v_2$ as a function of centrality. The shapes of the curves are similar to those of charged hadrons. However, different from the charged hadron case [29], the elliptic flow is more sensitive to the cross section. This is due to the increased sensitivity of radial flow of massive particles relative to light hadrons as seen in Fig. 2. Larger cross section has larger asymptotic elliptic flow at high $p_t$, at the same time it has larger $\langle p_t^2 \rangle$ which leads to more weight of high $p_t$ flow in the integrated $v_2$.

More details can be seen by looking at the $p_t$ distributions and the $p_t$ differential $v_2$ curves. They are shown in Fig. 4 for minimum-bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. In addition to the $J/\psi$ results, the charm quark and the $D$ meson (including $D^*$ meson) results are also shown. Being affected by both the charm and the light quarks, $D$ mesons have an invariant $p_t$ distribution that has the same concave shape as the charm quark distribution with a slightly higher averaged $p_t$. On the other hand, $J/\psi$ comes only from charm quarks. The $p_t$ distribution has a different, convex, shape, with a more enhanced averaged $p_t$. 

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The elliptic flow results show mass ordering for the low $p_t$ region. Charm and $D$ meson $v_2$ curves increase with $p_t$, reach a peak, then decrease a little. $J/\psi$ $v_2$ in the $p_t$ range shown here increases, crosses those of charm quarks and $D$ mesons up to a value that is comparable to the peak value of charm and $D$ meson elliptic flow. This behavior is different from some previous studies in which $J/\psi$ $v_2$ is consistently larger than $D$ meson $v_2$ \cite{49}. The crossing of the $J/\psi$ and $D$ meson $v_2$ curves reflects the distinct freeze-out phase space distributions from the AMPT model.

In summary, $J/\psi$ production from the coalescence of charm and anti-charm quarks reflects charm interactions in the QGP. The $J/\psi$ yield is very sensitive to the charm production cross section in $p+p$ collisions. Coalescence yield has a centrality dependence that is similar to that of recombination models. Both the 3mb and 10mb cases can lead to suppression on the same level as recombination models and consistent with preliminary PHENIX results. The 10mb case gives $\langle p_t^2 \rangle$ around 3 GeV$^2$ and is comparable to recombination results and preliminary PHENIX data, while the 3mb results are much lower than the 10mb case. The elliptic flow follows the same centrality dependence as charged hadrons, but is more sensitive to the cross section partly due to the enhanced sensitivity of $p_t$ distribution because of the large mass.

FIG. 3: Elliptic flow as a function of the number of participant nucleons.
FIG. 4: Invariant transverse momentum distributions and $p_t$ differential elliptic flows for charm quarks, $D$ mesons, and $J/\psi$ particles.

of the $J/\psi$ particle. The $J/\psi$ $p_t$ distribution is convex and different from that of $D$ mesons because of the combination of charm and anti-charm quarks. The $J/\psi$ elliptic flow crosses that of $D$ mesons and reaches about the peak value of the $D$ meson elliptic flow. Hence, the combination of open and hidden charm measurements will provide a more complete picture of the evolution of the charm quarks in the strongly interacting Quark-Gluon Plasma.

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