HADRONIC SCATTERINGS OF CHARM MESONS AND ENHANCEMENT OF INTERMEDIATE MASS DILEPTONS

ZIWEI LIN, CHE MING KO, BIN ZHANG
Cyclotron Institute and Physics Department,
Texas A&M University,
College Station, TX 77843-3366, USA

The scattering effects of charm mesons by hadrons such as the pion, rho meson and nucleon are studied in an effective Lagrangian, and are found to be important in heavy ion collisions. At the CERN-SPS energies, hadronic re scatterings are shown to harden the charm meson $m_T$ spectra, leading to a significant enhancement of the yield of intermediate-mass dimuons from charm meson decays.

1 Introduction

Heavy quark production in hadronic reactions is reasonably well described by perturbative QCD. However, in heavy ion collisions, final-state interactions may affect the spectra of produced heavy mesons. At the Relativistic Heavy Ion Collider (RHIC), a dense partonic system, often called the quark gluon plasma (QGP), is expected to be formed at the early stage. Since the QGP may induce a strong radiative energy loss of the produced heavy quarks, a change in the spectra of heavy meson observables could provide us information on the properties of the QGP. But interactions between heavy mesons and other hadrons may not be negligible and need to be studied.

Such a hadronic modification of the charm spectra in heavy ion collisions has been recently suggested as a possible explanation for the observed enhancement of dimuons of intermediate masses in the NA50 experiments at the CERN-SPS. Assuming that charm mesons develop a transverse flow due to rescatterings with hadrons, leading to a harder charm meson $m_\perp$ spectra, dimuons from charm meson decays are also found to have a harder $p_\perp$ spectrum. Based on the energy cuts for muons at the NA50 experiment, more dimuons would then be found to have an invariant mass above 1.5 GeV. Another explanation based on dilepton productions from secondary meson-meson interactions has also been proposed. Whether or not charm mesons acquire a transverse flow depends on how strongly charm mesons interact with other hadrons during their propagation through the matter. In this study, we shall evaluate the scattering cross sections of charm mesons with pion, rho, and nucleon, using an effective Lagrangian. The effects of hadronic scatterings on the charm meson transverse momentum spectra and dileptons from charm meson decays are then estimated for heavy ion collisions at CERN-SPS energies.
2 Charm meson interactions with hadrons

We consider the scattering of charm mesons ($D^+, D^-, D^0, D^{*+}, D^{*-}, D^{*0}$, and $\bar{D}^{*0}$) with pion, rho, and nucleon. If the $SU(4)$ symmetry were exact, interactions involving pseudo-scalar and vector mesons could be described by the following Lagrangian:

$$\mathcal{L}_{PV} = igTr \left( P^\dagger V^\mu \partial_\mu P \right) + h.c. \quad (1)$$

where $P$ and $V$ represent, respectively, the following $4 \times 4$ pseudo-scalar and vector meson matrices:

$$P = \begin{pmatrix}
\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} + \frac{\eta_c}{\sqrt{6}} & \pi^+ & K^+ & \bar{D}^0 \\
\pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} + \frac{\eta_c}{\sqrt{6}} & K^0 & D^- \\
K^- & \bar{K}^0 & -\eta V^{\frac{2}{3}} + \frac{\eta_c}{\sqrt{6}} & D_s^- \\
D^0 & D^+ & D_s^+ & -\frac{3\eta_c}{\sqrt{6}} \\
\end{pmatrix},$$

$$V = \begin{pmatrix}
\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{6}} + \frac{J/\psi}{\sqrt{3}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\
\rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{6}} + \frac{J/\psi}{\sqrt{3}} & K^{*0} & D^{*-} \\
K^{*-} & \bar{K}^{*0} & -\omega V^{\frac{2}{3}} + \frac{J/\psi}{\sqrt{6}} & D_s^{*-} \\
D^{*0} & D^{*+} & D_s^{*+} & \frac{3J/\psi}{\sqrt{6}} \\
\end{pmatrix}.$$ 

Expanding the Lagrangian in Eq.(1) in terms of the meson fields explicitly, we obtain the following Lagrangians for meson-meson interactions:

$$\mathcal{L}_{\pi DD} = -ig_{\pi DD} \bar{D}^\mu \bar{D}^\nu \cdot [D(\partial_\mu \bar{D}) - (\partial_\mu D)\bar{D}] + h.c.,$$

$$\mathcal{L}_{\rho DD} = -ig_{\rho DD} \bar{D} \partial_\mu \bar{D} (\partial_\mu D) \cdot \bar{\rho}^\mu,$$

$$\mathcal{L}_{\rho \rho} = g_{\rho \rho} \bar{\rho}^\mu \cdot (\bar{\rho} \times \partial_\mu \bar{D}).$$

We also need the following Lagrangians for meson-baryon interactions:

$$\mathcal{L}_{\pi NN} = -ig_{\pi NN} \bar{N} \gamma_5 \bar{\tau} N \cdot \bar{\pi},$$

$$\mathcal{L}_{\rho NN} = g_{\rho NN} \bar{N} \left( \gamma^\mu \bar{\tau} \cdot \bar{\rho}_\mu + \frac{K_{\rho}}{2m_N} \sigma^{\mu\nu} \bar{\tau} \cdot \partial_\mu \bar{\rho}_\nu \right) N.$$ 

Fig.1 shows the Feynman diagrams considered in this study for charm meson interactions with the pion (diagrams 1 to 8), the rho meson (diagrams 9 and 10), and the nucleon (diagrams 11 to 13). The differential cross sections of these processes can be found in the reference. Possible interferences among diagrams 3, 4 and 8 have not been included.
For coupling constants, we take $g_{\rho\pi\pi} = 6.1$, $g_{\pi DD^*} = 4.4$, $g_{\rho DD} = 2.8$, $g_{\pi NN} = 13.5$, $g_{\rho NN} = 3.25$, and $\kappa_\rho = 6.1$. The $SU(4)$ symmetry assumed in the Lagrangian in Eq.(1) would give the following relations:

$$g_{\pi KK}(3.3) = g_{\pi DD^*}(4.4) = g_{\rho KK}(3.0) = g_{\rho DD}(2.8) = \frac{g_{\phi KK}}{\sqrt{2}}(3.4) = \frac{g_{\rho\pi\pi}}{2}(3.0).$$

The empirical values given in parentheses agree reasonably well with this prediction even though the $SU(4)$ symmetry is badly broken. Form factors are introduced at the vertices to take into account the structure of hadrons. For $t$-channel vertices, monopole form factors of the form $f(t) = (\Lambda^2 - m_\alpha^2) / (\Lambda^2 - t)$ are used, where $\Lambda$ is a cut-off parameter, and $m_\alpha$ is the mass of the exchanged meson. It should be noted that the cross sections for diagrams 2 and 9 ($D^*\pi \leftrightarrow D\rho$) are singular because the intermediate mesons can be on-shell. In the present study, we simply add an imaginary part of 50 MeV to the mass of the intermediate pion as the regulator.

The thermal averaged cross section, $<\sigma v>$, is shown in Fig.2(a) for initial particles with a thermal distribution at temperature $T$. Only the dominant scattering channels which have values above 1.1 mb are shown.

3 Estimates of Rescattering Effects

In this section, we estimate the effects of hadronic rescatterings on both the charm meson $m_\perp$ spectra and the invariant mass distribution of dileptons from charm meson decays in heavy ion collisions at SPS energies.

We first determine the squared momentum transfer to a charm meson, $p_0^2$, as the squared momentum of the final charm meson $D_2$ in the rest frame of $D_1$ for a scattering process $D_1X_1 \rightarrow D_2X_2$. In the charm meson local frame, we assume the time evolution of the hadron densities as $\rho(\tau) \propto 1/\tau$. Then the total number of scatterings for a charm meson is given by

$$N = \int_{\tau_0}^{\tau_f} \sigma v p_\perp d\tau \simeq \sigma v p_0 \tau_0 \ln \left( \frac{R_{Am}^{D_1} D_1}{\tau_0 p_\perp} \right),$$
and the squared total momentum transfer from hadronic scatterings is

\[< p_0^2 > = < N p_0^2 > = \sum_{i=\pi,\rho,N,...} < \sigma v p_0^2 >_i \rho_{i0} \ln \left( \frac{R_A < m_D^0 >}{\tau_0 < p_{i0}^2 >} \right).\]

Thus, the relevant quantity is the thermal average \(< \sigma v p_0^2 >\) instead of the usual \(<\sigma v>\). Fig. 2(b) shows this thermal average for the dominant scattering channels which have values above 0.75 mb·GeV². Summing up contributions from all scattering channels in Fig. 2(a), (b) and (c) separately, and simply dividing by 2 to account for the average over \(D\) and \(D^*\), we get

\(< \sigma v p_0^2 > \simeq 1.1, 1.5\) and 2.7 mb·GeV² at \(T = 150\) MeV

for \(\pi\), \(\rho\) and \(N\) scatterings with charm mesons, respectively.

For central \(Pb + Pb\) collisions at SPS energies, the initial total numbers of particles are about 500(\(\pi\)), 220(\(\rho\)), 100(\(\omega\)), 80(\(\eta\)), 180(\(N\)), 60(\(\Delta\)), and 130(higher baryon resonances). We have not calculated the scattering cross sections between charm mesons and hadrons such as kaons, \(\omega\), \(\eta\), \(\Delta\), and higher baryon resonances. For a conservative estimate of the effect, we only include \(\pi\), \(\rho\) and nucleon, and we obtain

\(\rho_0\tau_0 \simeq 0.79(\pi), 0.35(\rho), \) and 0.28(nucleon) fm⁻²,

\(\Rightarrow < p_0^2 > \simeq 0.61 \text{ GeV}^2 \Rightarrow T_S = 96 \text{ MeV}.\)

In the above, we have taken \(\tau_0 = 1\) fm. The parameter \(T_S\) characterizes the scattering strength and is given by \(T_S \simeq < p_0^2 >/(3m_D)\) in the lowest-order
approximation. Based on Monte Carlo simulations, $T_S$ has been related to the inverse slope $T_{\text{eff}}$ of the final charm meson $m_{\perp}$ spectrum, and this is shown in Fig. 6 of Ref. 1. From that figure, we find that the charm meson $T_{\text{eff}}$ increases from 160 MeV to about 235 MeV, leading to a dimuon enhancement factor of about 2.1 for the NA50 acceptance.

For heavy ion collisions at RHIC energies, in addition to hadronic rescatterings of charm mesons, partonic rescattering effects on charm quarks also need to be included. Furthermore, radiative processes of charm quarks inside the QGP would further complicate the issue as they may cause energy loss and soften the charm meson $m_{\perp}$ spectra. More studies are thus needed before one can make predictions for RHIC.

4 Discussions and Summary

From our calculated scattering cross sections of charm mesons with hadrons such as pion, rho meson and nucleon, we have given an estimate of the rescattering effect at the SPS energies. We find that hadronic rescatterings in heavy ion collisions are likely to have a significant effect on charm meson spectra, and also the dilepton spectra from charm meson decays.

The estimates given above are, however, based on a simple assumption on the time evolution of the hadronic system, which enables us to make a more analytical estimate for the rescattering effects. For a quantitative study of the rescattering effects on charm meson observables, studies with a partonic and hadronic cascade program are much needed as the time evolution and the chemical equilibration of the dense system are better simulated in such a model.

Acknowledgments

This work was supported by the National Science Foundation under Grant No. PHY-9870038, the Welch Foundation under Grant No. A-1358, and the Texas Advanced Research Project FY97-010366-068.

References

1. Z. Lin and X.-N. Wang, Phys. Lett. B 444, 245 (1998).
2. G.Q. Li and C. Gale, Nucl. Phys. A 638, 491c (1998).
3. Z. Lin, C.M. Ko and B. Zhang, preprint nucl-th/9905003.
4. S.G. Matinyan and B. M"uller, Phys. Rev. C 58, 2994 (1998).
5. G.Q. Li et al, Nucl. Phys. A 611, 539 (1996).