Thermal Dilepton Production from Dropping $\rho$
in the Vector Manifestation

Masayasu Harada

Department of Physics, Nagoya University, Nagoya, 464-8602, Japan
harada@hken.phys.nagoya-u.ac.jp

Chihiro Sasaki

GSI, D-64291 Darmstadt, Germany
c.sasaki@gsi.de

Received (received date)
Revised (revised date)

We study the pion electromagnetic form factor and the dilepton production rate in hot
matter based on the vector manifestation (VM) of chiral symmetry in which the massless
vector meson becomes the chiral partner of the pion, giving a theoretical framework of
the dropping $\rho$ à la Brown-Rho scaling. The VM predicts a strong violation of the
vector dominance (VD) near the phase transition point associated with the dropping $\rho$.
We present the effect of the VD violation to the dilepton production rate and make a
comparison to the one predicted by assuming the VD together with the dropping $\rho$.

1. Introduction

An enhancement of dielectron mass spectra below the $\rho/\omega$ resonance was first ob-
served at CERN SPS\cite{1} and it is considered as an indication of the medium mod-
ification of the vector mesons. Still the vector meson mass in matter remains an
open issue\cite{2,3,4,5}. Although several scenarios like collisional broadening due to
interactions with the surrounding hot and dense medium\cite{6} and dropping $\rho$ meson
mass associated with chiral symmetry restoration\cite{7,8,9,10,11} have been discussed, there are
conceivable ambiguities which have not been considered\cite{9,10,11} and no conclusive
distinction between them has been done.

The vector manifestation (VM)\cite{8,12} was proposed as a novel pattern of the
Wigner realization of chiral symmetry with a large number of massless quark flavors
by using the hidden local symmetry (HLS) theory, in which the vector meson be-
comes massless at the restoration point and belongs to the same chiral multiplet as
the pion, i.e., \textit{the massless vector meson is the chiral partner of the pion}. The stud-
ies of the VM in hot/dense matter have been carried out\cite{13,14,15} and the VM was
also applied to construct an effective Lagrangian for the heavy-light mesons which
can well describe the recent experimental observation on the $D(0^+, 1^+)$ mesons\cite{16}.
It has been shown that the vector dominance (VD) of the electromagnetic form factor of the pion is accidentally satisfied in $N_f = 3$ QCD at zero temperature and zero density, and that it is strongly violated in large $N_f$ QCD when the VM occurs. The VD is characterized by the direct $\gamma\pi\pi$ being zero. In hot/dense matter, the $\gamma\pi\pi$ coupling is modified by medium effects and approaches $1/2$ with increasing $T/\mu_q$ toward the critical point, which is due to the intrinsic $T/\mu_q$ effects associated with the chiral symmetry restoration. This implies that the VD is strongly violated near the critical point, maximally by 50%. It strongly affects the understanding of experiments on the dilepton productions based on the dropping $\rho$, and recently a quantitative study has been done. In this contribution, we focus on the electromagnetic form factor of pion and the dilepton production rate at finite temperature from the dropping $\rho$ based on the VM with paying a special attention to the effect of the violation of the VD following Ref.

2. Form factor and dilepton spectra

In Ref. the bare parameters of the HLS Lagrangian were determined by performing the Wilsonian matching, in which the axial-vector and vector current correlators derived from the HLS with those by the operator product expansion in QCD are matched at a matching scale $\Lambda \sim 1$ GeV. This procedure in hot matter provides the following proportionality between the $\rho$-meson mass and the chiral condensate near $T_c$:

$$m_\rho(T) \propto \langle \bar{q}q \rangle_T ,$$

This implies that $m_\rho$ is thermally evolved following the temperature dependence of the quark condensate, which is nothing but the intrinsic temperature effect.

It should be stressed that Eq. holds only in the vicinity of $T_c$ and is not valid any more far away from $T_c$ where ordinary hadronic corrections are dominant. For expressing a temperature above which the intrinsic effect becomes important, we shall introduce a temperature $T_f$, so-called flash temperature. The VM and therefore the dropping $\rho$ mass become transparent for $T > T_f$. On the other hand, we expect that the intrinsic effects are negligible in the low-temperature region below $T_f$: Only hadronic thermal corrections are considered for $T < T_f$. Here we would like to remark that the Brown-Rho scaling deals with the quantity directly locked to the quark condensate and hence the scaling masses are achieved exclusively by the intrinsic effect in the present framework.

A lepton pair is emitted from the hot/dense matter through a decaying virtual photon. The differential production rate in the medium for fixed temperature $T$ is expressed in terms of the imaginary part of the photon self-energy $\text{Im}\Pi$ as

$$\frac{dN}{d\vec{q}}(q_0, \vec{q}; T) = \frac{\alpha^2}{\pi^3 M^2} \frac{1}{e^{q_0/T} - 1} \text{Im}\Pi(q_0, \vec{q}; T) ,$$

where $\alpha = e^2/4\pi$ is the electromagnetic coupling constant, $M$ is the invariant mass of the produced dilepton and $q_\mu = (q_0, \vec{q})$ denotes the momentum of the virtual
Thermal Dilepton Production from Dropping $\rho$ in the Vector Manifestation

![Diagram](image_url)

Fig. 1. Electromagnetic form factor of the pion as a function of the invariant mass $\sqrt{s}$ for several temperatures. The curves in the left panel (a) include only the hadronic temperature effects and those in the right panel (b) include both intrinsic and hadronic temperature effects.

We will focus on an energy region around the $\rho$ meson mass scale in this analysis. In this energy region it is natural to expect that the photon self-energy is dominated by the two-pion process and its imaginary part is related to the pion electromagnetic form factor $F(s; T)$ through

$$\text{Im}\Pi(s; T) = \frac{1}{6\pi\sqrt{s}} \left( s - 4m^2_\pi \right)^{3/2} |F(s; T)|^2,$$

where $s$ is the square of the invariant mass and $m_\pi$ is the pion mass.

Figure 1 shows the pion electromagnetic form factor $F$ for several temperatures. In Fig. 1 (a) there is no remarkable shift of the $\rho$ meson mass but the width becomes broader with increasing temperature, which is consistent with the previous study in Ref. 22. In Fig. 1 (b) the intrinsic temperature effect are also included into all the parameters in the form factor. At the temperature below $T_f$, the hadronic effect dominates the form factor, so that the curves for $T = 0$, $0.4T_c$, and $0.6T_c$ agree with the corresponding ones in Fig. 1(a). At $T = T_f$ the intrinsic effect starts to contribute and thus in the temperature region above $T_f$ the peak position of the form factor moves as $m_\rho(T) \to 0$ with increasing temperature toward $T_c$. Associated with this dropping $\rho$ mass, the width becomes narrow and the value of the form factor at the peak grows up.

As noted, the VM leads to the strong violation of the vector dominance (VD) (indicated by $\nabla\sigma$) near the chiral symmetry restoration point, which can be traced through the Wilsonian matching and the renormalization group evolutions. Figure 2 shows the form factor and the dilepton production rate integrated over three-momentum, in which the results with VD and $\nabla\sigma$ were compared. It can be easily seen that the $\nabla\sigma$ gives a reduction compared to the case with keeping the VD. Below $T_f$ there are no much differences, while above $T_f$ a shift of the $\rho$ meson mass to lower-mass region can be seen since the intrinsic temperature effects are turned on. The form factor, which becomes narrower with increasing temperature due to the dropping $m_\rho$, exhibits an obvious discrepancy between the cases with VD and $\nabla\sigma$. The production rate based on the VM (i.e., the case with $\nabla\sigma$) is...
Fig. 2. Electromagnetic form factor of the pion (left) and dilepton production rate (right) as a function of the invariant mass $\sqrt{s}$ for various temperatures. The solid lines include the effects of the violation of the VD. The dashed-dotted lines correspond to the analysis assuming the VD. In the dashed curves in the right-hand figures, the parameters at zero temperature were used.

suppressed compared to that with the VD. One observes that the suppression is more transparent for larger temperature.
As one can see in (c), the peak value of the rate predicted by the VM in the temperature region slightly above the flash temperature is even smaller than the one obtained by the vacuum parameters, and the shapes of them are quite similar to each other. This indicates that it might be difficult to measure the signal of the dropping $\rho$ experimentally, if this temperature region is dominant in the evolution of the fireball. In the case shown in (d), on the other hand, the rate by VM is enhanced by a factor of about two compared with the one by the vacuum $\rho$. The enhancement becomes prominent near the critical temperature as seen in (e). These imply that we may have a chance to discriminate the dropping $\rho$ from the vacuum $\rho$.

3. Summary and discussions

We explored the electromagnetic form factor of pion and the dilepton production rate in the vector manifestation (VM) of chiral symmetry using the hidden local symmetry (HLS) theory at finite temperature. This framework involves the intrinsic temperature effect of the Lagrangian parameters which leads to the dropping $m_\rho$ as the VM. The form factor and the dilepton production rate receive non-negligible contributions from the intrinsic effects.

A naive dropping $m_\rho$ formula, i.e., $T_f = 0$, as well as VD in hot/dense matter are sometimes used for theoretical implications of the data. As we have shown here, the intrinsic temperature effects together with the violation of the VD give a clear difference from the results without including those effects. It may be then expected that a field theoretical analysis of the dropping $\rho$ and a reliable comparison to dilepton measurements will provide an evidence for the in-medium hadronic properties associated with the chiral symmetry restoration, if complicated hadronization processes do not wash out those changes.

Our analysis can be applied to a study at finite density. Especially to study under the conditions for CERN/SPS and future GSI/FAIR would be an important issue. In such a dense environment, the particle-hole configurations with same quantum numbers with pions and $\rho$ mesons are crucial. The violation of the VD has been also presented at finite density in the HLS theory. Therefore the dilepton rate as well as the form factor will be much affected by the intrinsic density effects and be reduced above the “flash density”. Nuclear many-body effects may provide a broadening and it would be important to study what happens on the dilepton production if one includes both mass shift and collisional broadening.

Recently the chiral perturbation theory with including vector and axial-vector mesons as well as pions has been constructed based on the generalized HLS. In this theory the dropping $\rho$ and $A_1$ meson masses were formulated and it was shown that the dropping masses are related to the fixed points of the RGEs, one of which gives a VM-type restoration and that the VD is strongly violated also in this case. It was proposed that the dropping axial-vector mesons can explain the anomalous $\rho^0/\pi^-$ ratio measured in peripheral collisions by STAR. Based on a
field theoretical way, inclusion of the effect of $A_1$ meson will be interesting.

Acknowledgments

The work of C.S. was supported in part by the Virtual Institute of the Helmholtz Association under the grant No. VH-VI-041. The work of M.H. is supported in part by the Daiko Foundation #9099, the 21st Century COE Program of Nagoya University provided by Japan Society for the Promotion of Science (15COEG01), and the JSPS Grant-in-Aid for Scientific Research (c) (2) 16540241.

References

1. G. Agakishiev et al. [CERES Collaboration], Phys. Rev. Lett. 75 (1995) 1272.
2. K. Ozawa et al. [E325 Collaboration], Phys. Rev. Lett. 86 (2001) 5019; M. Naruki et al., Phys. Rev. Lett. 96 (2006) 092301.
3. D. Trnka et al. [CBELSA/TAPS Collaboration], Phys. Rev. Lett. 94 (2005) 192303.
4. E. V. Shuryak and G. E. Brown, Nucl. Phys. A 717 (2003) 322.
5. S. Damjanovic et al. [NA60 Collaboration], J. Phys. G 31 (2005) S903; R. Arnaldi et al. [NA60 Collaboration], Phys. Rev. Lett. 96, 162302 (2006).
6. R. Rapp and J. Wambach, Adv. Nucl. Phys. 25 (2000) 1; R. Rapp, arXiv:nucl-th/0701082.
7. G. E. Brown and M. Rho, Phys. Rev. Lett. 66 (1991) 2720.
8. M. Harada and K. Yamawaki, Phys. Rev. Lett. 86 (2001) 757.
9. G. E. Brown and M. Rho, arXiv:nucl-th/0509001; arXiv:nucl-th/0509002.
10. H. van Hees and R. Rapp, arXiv:hep-ph/0604269.
11. B. Schenke and C. Greiner, Phys. Rev. Lett. 98, 022301 (2007).
12. M. Harada and K. Yamawaki, Phys. Rept. 381 (2003) 1.
13. M. Harada and C. Sasaki, Phys. Lett. B 537 (2002) 280.
14. M. Harada, Y. Kim and M. Rho, Phys. Rev. D 66 (2002) 016003.
15. M. Harada and C. Sasaki, Nucl. Phys. A 736 (2004) 300; M. Harada, Y. Kim, M. Rho and C. Sasaki, Nucl. Phys. A 727 (2003) 437; C. Sasaki, Nucl. Phys. A 739 (2004) 151; M. Harada, Y. Kim, M. Rho and C. Sasaki, Nucl. Phys. A 730 (2004) 379; M. Harada, M. Rho and C. Sasaki, arXiv:hep-ph/0506092.
16. M. Harada, M. Rho and C. Sasaki, Phys. Rev. D 70 (2004) 074002.
17. J. J. Sakurai, Currents and Mesons, University of Chicago Press, Chicago (1969).
18. M. Harada and K. Yamawaki, Phys. Rev. Lett. 87 (2001) 152001.
19. M. Harada and C. Sasaki, Phys. Rev. D 74, 114006 (2006).
20. G. E. Brown, C. H. Lee and M. Rho, Nucl. Phys. A 747 (2005) 530.
21. G. E. Brown, C. H. Lee and M. Rho, Phys. Rev. C 74 (2006) 024906.
22. C. Song and V. Koch, Phys. Rev. C 54 (1996) 3218.
23. B. Friman and H. J. Pirner, Nucl. Phys. A 617 (1997) 496.
24. M. Harada and C. Sasaki, Phys. Rev. D 73 (2006) 036001; Y. Hidaka, O. Morimatsu and M. Ohtani, Phys. Rev. D 73 (2006) 036004.
25. J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 92 (2004) 092301.