

## Vector-Axialvector Mixing in Hot Matter and Its Hadronic Effective Field Theory Description

Chihiro SASAKI,<sup>1</sup> Masayasu HARADA<sup>2</sup> and Wolfram WEISE<sup>1</sup>

<sup>1</sup>*Physik-Department, Technische Universität München,  
D-85747 Garching, Germany*

<sup>2</sup>*Department of Physics, Nagoya University, Nagoya 464-8602, Japan*

We discuss the importance of the axialvector meson in chiral phase transition at finite temperature. We show that there exists a significant contribution in the vector spectral function from the axialvector meson through the vector-axialvector mixing in hot matter.

### §1. Introduction

Changes of hadron properties are expected to be indications of the tendency towards chiral symmetry restoration in hot and/or dense QCD. In particular, the short-lived vector mesons like the  $\rho$  mesons are expected to carry information on the modifications of hadrons in matter.<sup>1)</sup> In the presence of hot matter the vector and axialvector current correlators are mixed due to the pion in the heat bath, and a process is described in a model-independent way at low temperatures as a low-energy theorem of chiral symmetry.<sup>2)</sup> The vector spectral function is then modified by axialvector mesons through the mixing theorem.<sup>3),4)</sup>

The validity of the theorem is, however, limited to temperatures  $T < 2f_\pi$ , where  $f_\pi$  is the pion decay constant in vacuum. At higher temperatures hadrons other than pions are thermally activated. Thus one needs in-medium correlators systematically involving those excitations. In this contribution we show the effects of the mixing (hereafter V-A mixing) and how the axialvector mesons affect the spectral function near the chiral phase transition within an effective field theory.

### §2. Role of axialvector mesons

Several models exist which explicitly include the axialvector meson in addition to the pion and vector meson consistently with the chiral symmetry of QCD, such as the Massive Yang-Mills theory,<sup>5)</sup> the anti-symmetric tensor field method<sup>6)</sup> and the model based on the generalized hidden local symmetry (GHLS).<sup>7),8)</sup> These models are equivalent<sup>8),9)</sup> for tree-level amplitudes in low-energy limit. Recently a systematic perturbation scheme based on the GHLS has been constructed.<sup>10),11)</sup> In this approach the Weinberg sum rules<sup>12)</sup> are stable against the renormalization group evolution at one-loop.<sup>10),\*)</sup>

---

\*) The GHLS Lagrangian does not include  $\bar{q}q$  scalar modes which are assumed to be heavier than other mesons incorporated. This may not be true near the critical point within the Ginzburg-Landau picture of the phase transition. The scalar mesons thus modify the renormalization group structure.

The critical temperature is defined as the temperature at which the vector and axialvector current correlators coincide. When these correlators are saturated by the lowest lying meson, we have<sup>10)</sup>

$$G_A - G_V \propto M_\rho^2(M_{a_1}^2 - M_\rho^2) = M_\rho^2 \delta M^2. \quad (2.1)$$

Then the chiral symmetry restoration implies that either  $\delta M = 0$  or  $M_\rho = 0$  (or both): Either the  $\rho$ - $a_1$  mass difference  $\delta M$  or the  $\rho$  meson mass is identified with a measure of the spontaneous chiral symmetry breaking and acts as an order parameter of the chiral phase transition. We consider  $\delta M$  changing with temperature intrinsically such that one has  $G_A - G_V = 0$  at the chiral transition.

Thus, the *bare* axialvector meson mass depends on temperature as

$$M_{a_1}^2 = M_\rho^2 + \delta M^2(T). \quad (2.2)$$

Note that the dropping masses following the Brown-Rho scaling<sup>13)</sup> are achieved if the bare  $\rho$  mass goes to zero at the critical point, which is indeed the case in the vector manifestation (VM) scenario.<sup>14)</sup>

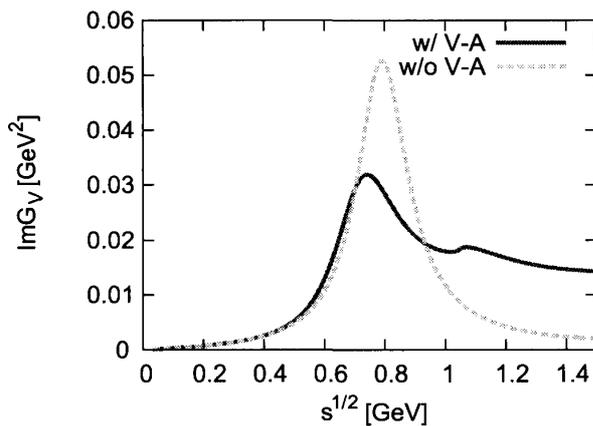


Fig. 1. The vector spectral function at temperature  $T/T_c = 0.85$  with the critical temperature  $T_c = 200$  MeV, calculated in the  $\rho$ -meson rest frame. The solid curve is obtained in the full calculation. The dashed line is calculated eliminating the axialvector meson from the theory.

We show the spectral function of the vector current correlator calculated in the GHLS theory in Fig. 1. Two cases are compared; one includes the V-A mixing and the other does not. The spectral function has a peak at  $M_\rho$  and a bump around  $M_{a_1}$  due to the mixing. The height of the spectrum at  $M_\rho$  is enhanced and a contribution above  $\sim 1$  GeV is gone when one omits the  $a_1$  in the calculation. In Fig. 2 we show the temperature dependence of the vector spectral function. One observes a systematic downward shift of the enhancement around the  $a_1$  mass with temperature, and  $M_{a_1}$  comes together with  $M_\rho$  at  $T_c$ . The V-A mixing eventually vanishes there which is a direct consequence of vanishing coupling of  $a_1$  to  $\rho$ - $\pi$ . This

feature is unchanged even if an explicit scalar field is present.<sup>15)</sup>

In case of dropping  $\rho$  and  $a_1$  masses, the spectral function is enhanced compared to that without mass dropping since the  $\rho$  decay width is narrower<sup>16)</sup> as shown in Fig. 3. The feature that the  $a_1$  meson suppresses the spectral function through the V-A mixing is unchanged. It should be noted that the vector meson becomes the chiral partner of the pion and vector meson dominance is strongly violated when the chiral symmetry is restored in the VM.<sup>14)</sup> This induces a significant reduction of the vector spectral function.<sup>16),17)</sup> On the other hand, the pion form factor is still vector-meson dominated at  $T_c$  if the dropping  $\rho$  and  $a_1$  join in the same chiral multiplet.<sup>10)</sup>

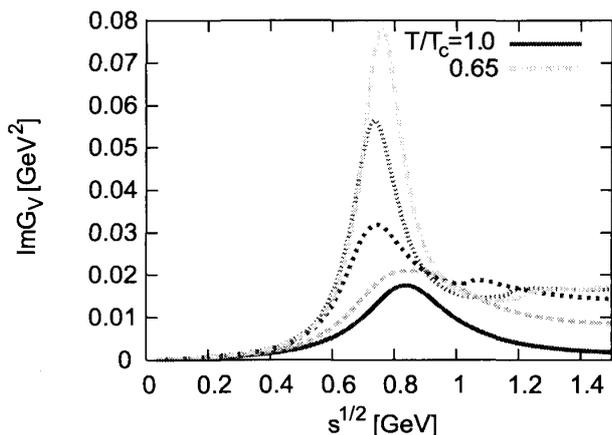


Fig. 2. The vector spectral function at several temperatures  $T/T_c = 0.65$ – $1.0$  in steps of  $0.1$  (from top to bottom).

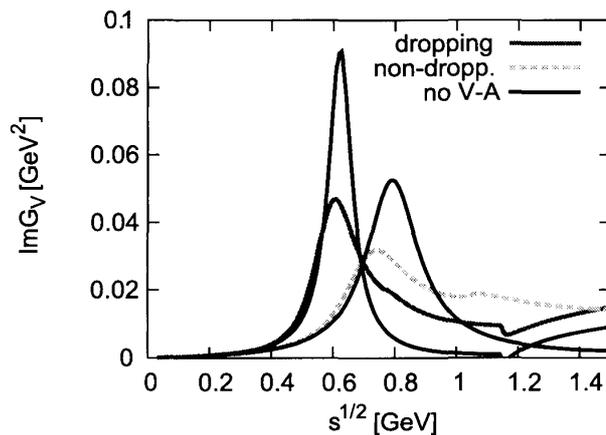


Fig. 3. The vector spectral function at temperature  $T/T_c = 0.85$  with dropping (solid) and non-dropping (dashed)  $\rho$  bare mass. The black solid lines indicate the results eliminating the  $a_1$  mesons.

### §3. Conclusions

We have performed a systematic study of the V-A mixing in the current correlation functions and its evolution with temperature. The axialvector meson contributes significantly to the vector spectral function; the presence of the  $a_1$  reduces the vector spectrum around  $M_\rho$  and enhances it around  $M_{a_1}$ .

One interesting application of this thermal spectral function is to study dilepton production in relativistic heavy-ion collisions. The change of the  $a_1$ -meson properties and V-A mixing near the critical point has not been properly treated so far in dilepton processes in the context of the chiral phase transition. In order to deal with the dileptons one needs to account for other collective excitations and many-body interactions as well as the time evolution of a created fireball.<sup>18)</sup> Such effects can screen signals of chiral restoration<sup>17)</sup> and make an interpretation of broad in-medium spectral functions in terms of a changing chiral order parameter quite difficult.<sup>19)</sup> The situation at RHIC and/or LHC might be very different from SPS. At SPS energies many-body effects come from the presence of baryons. These effects are expected to be much reduced in very hot matter with relatively low baryon density. The present study may then be of some relevance for the high temperature, low baryon density scenarios encountered at RHIC and LHC.

### Acknowledgements

The work supported in part by BMBF and by the DFG cluster of excellence “Origin and Structure of the Universe”.

### References

- 1) See, e.g., V. Bernard and U. G. Meissner, Nucl. Phys. A **489** (1988), 647.  
T. Hatsuda and T. Kunihiro, Phys. Rep. **247** (1994), 221.

- R. D. Pisarski, hep-ph/9503330.  
 F. Klingl, N. Kaiser and W. Weise, Nucl. Phys. A **624** (1997), 527.  
 R. Rapp and J. Wambach, Adv. Nucl. Phys. **25** (2000), 1.  
 F. Wilczek, hep-ph/0003183.  
 G. E. Brown and M. Rho, Phys. Rep. **363** (2002), 85.
- 2) M. Dey, V. L. Eletsky and B. L. Ioffe, Phys. Lett. B **252** (1990), 620.
  - 3) E. Marco, R. Hofmann and W. Weise, Phys. Lett. B **530** (2002), 88.
  - 4) M. Urban, M. Buballa and J. Wambach, Phys. Rev. Lett. **88** (2002), 042002.
  - 5) See, e.g., J. Schwinger, Phys. Lett. B **24** (1967), 473.  
 J. Schwinger, *Particles and Sources* (Gordon and Breach, New York, 1969).  
 J. Wess and B. Zumino, Phys. Rev. **163** (1967), 1727.  
 S. Gasiorowicz and D. A. Geffen, Rev. Mod. Phys. **41** (1969), 531.  
 O. Kaymakcalan, S. Rajeev and J. Schechter, Phys. Rev. D **30** (1984), 594.
  - 6) J. Gasser and H. Leutwyler, Ann. of Phys. **158** (1984), 142.  
 G. Ecker, J. Gasser, A. Pich and E. de Rafael, Nucl. Phys. B **321** (1989), 311.
  - 7) M. Bando, T. Kugo and K. Yamawaki, Nucl. Phys. B **259** (1985), 493.  
 M. Bando, T. Fujiwara and K. Yamawaki, Prog. Theor. Phys. **79** (1988), 1140.
  - 8) N. Kaiser and U. G. Meissner, Nucl. Phys. A **519** (1990), 671.
  - 9) See, e.g., K. Yamawaki, Phys. Rev. D **35** (1987), 412.  
 U. G. Meissner and I. Zahed, Z. Phys. A **327** (1987), 5.  
 M. F. Golterman and N. D. Hari Dass, Nucl. Phys. B **277** (1986), 739.  
 G. Ecker, J. Gasser, H. Leutwyler, A. Pich and E. de Rafael, Phys. Lett. B **223** (1989), 425.  
 M. Tanabashi, Phys. Lett. B **384** (1996), 218.
  - 10) M. Harada and C. Sasaki, Phys. Rev. D **73** (2006), 036001.
  - 11) Y. Hidaka, O. Morimatsu and M. Ohtani, Phys. Rev. D **73** (2006), 036004.
  - 12) S. Weinberg, Phys. Rev. Lett. **18** (1967), 507.
  - 13) G. E. Brown and M. Rho, Phys. Rev. Lett. **66** (1991), 2720.
  - 14) M. Harada and K. Yamawaki, Phys. Rev. Lett. **86** (2001), 757; Phys. Rep. **381** (2003), 1.
  - 15) M. Harada, C. Sasaki and W. Weise, in progress.
  - 16) M. Harada and C. Sasaki, Phys. Rev. D **74** (2006), 114006.
  - 17) G. E. Brown, M. Harada, J. W. Holt, M. Rho and C. Sasaki, arXiv:0804.3196.
  - 18) H. van Hees and R. Rapp, hep-ph/0604269; arXiv:0711.3444.  
 J. Ruppert and T. Renk, Eur. Phys. J. C **49** (2007), 219.  
 R. Rapp, J. of Phys. G **34** (2007), S405.  
 H. van Hees, arXiv:0804.4493.
  - 19) Y. Kwon, M. Procura and W. Weise, arXiv:0803.3262.