Role of axial-vector mesons near the chiral phase transition

Chihiro Sasaki\textsuperscript{a}, Masayasu Harada\textsuperscript{b} and Wolfram Weise\textsuperscript{a}

\textsuperscript{a}Physik-Department, Technische Universität München, D-85747 Garching, Germany
\textsuperscript{b}Department of Physics, Nagoya University, Nagoya, 464-8602, Japan

Abstract

We present a systematic study of the vector–axial-vector mixing (V-A mixing) in the current correlation functions and its evolution with temperature within an effective field theory. The $a_1$-$\rho$-$\pi$ coupling vanishes at the critical temperature $T_c$ and thus the V-A mixing also vanishes. A remarkable observation is that even for finite $m_\pi$ the $\rho$ and $a_1$ meson masses are almost degenerate at $T_c$. The vanishing V-A mixing at $T_c$ stays approximately intact.

Key words: Vector–axial-vector mixing in hot matter, Chiral symmetry restoration

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In the presence of hot matter the vector and axial-vector current correlators are mixed due to pions in the heat bath. At low temperatures this process is described in a model-independent way in terms of a low-energy theorem based on chiral symmetry and consequently the vector spectral function is modified by axial-vector mesons through the mixing theorem \cite{1}. The validity of the theorem is, however, limited to temperatures $T \ll 2f_\pi$, where $f_\pi$ is the pion decay constant in vacuum. At higher temperatures one needs in-medium correlators systematically involving hadronic excitations other than pions. In this contribution we show the effects of the mixing (hereafter V-A mixing), and how the axial-vector mesons affect the vector spectral function near the chiral phase transition, within an effective field theory \cite{2}.

A model based on the generalized hidden local symmetry (GHLS) describes a system including the axial-vector meson explicitly, in addition to the pion and the vector meson, consistently with the chiral symmetry of QCD \cite{3}. We will use the GHLS Lagrangian as a reliable basis which describes the spectral function sum rules \cite{4}.

The critical temperature $T_c$ for the restoration of chiral symmetry in its Wigner-Weyl realization is defined as the temperature at which the vector and axial-vector current correlators, $G_V$ and $G_A$, coincide and their spectra become degenerate. Thus, chiral
symmetry restoration implies $\delta G = G_A - G_V = 0$ at $T_c$. Let us consider $\delta G$ changing with temperature intrinsically. To achieve $\delta G = 0$ at the critical temperature, we assume non-dropping $\rho$ mass at $T_c$ and adopt the following ansatz of the temperature dependence of the bare axial-vector meson mass, $M_{a_1}^2(T) = M_{\rho}^2 + \delta M^2(T)$:

$$\delta M^2(T) = \delta M^2(T = 0)\Theta(T_f - T) + \delta M^2(T = 0)\Theta(T - T_f)\frac{T_c^2 - T^2}{T_c^2 - T_f^2},$$  \hspace{1cm} (1)$$

where we schematically introduce the “flash temperature” which controls how the mesons experience partial restoration of chiral symmetry. The values of $T_c$ and $T_f$ are taken in a reasonable range as indicated, for example, by the onset of the chiral crossover transition observed in lattice QCD \cite{5}: $T_c = 200$ MeV and $T_f = 140$ MeV.

Figure 1 (left) shows the vector spectral function in the chiral limit. 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 broad 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. A difference between the two curves becomes more significant above $T_f$ where partial restoration of chiral symmetry sets in. For finite $m_\pi$ the energy of the time-like virtual $\rho$ meson splits into two branches corresponding to the processes, $\rho + \pi \rightarrow a_1$ and $\rho \rightarrow a_1 + \pi$, with thresholds $\sqrt{s} = M_{a_1} - m_\pi$ and $\sqrt{s} = M_{a_1} + m_\pi$. This results in the threshold effects seen as a shoulder at $\sqrt{s} = M_{a_1} - m_\pi$ and a bump above $\sqrt{s} = M_{a_1} + m_\pi$ in Fig. 1 (right). Note that the enhancement of the spectrum for $m_\pi \neq 0$ is due to the change of the phase space factor $(s - 4m_\pi^2)^{3/2}$.

Figure 2 (left) shows the temperature dependence of the vector spectral function in the chiral limit. One observes a systematic downward shift of the $a_1$ enhancement with increasing temperature, while the peak position corresponding to the $\rho$ pole mass moves upward. At $T/T_c = 0.9$ the two bumps begin to overlap: the lower one corresponds to the $\rho$ pole, and the upper one to the $a_1-\pi$ contribution. Finally at $T = T_c$, $M_{a_1}$ becomes degenerate with $M_{\rho}$ around $\sqrt{s} \simeq 1$ GeV and the two bumps are on top of each other. The V-A mixing eventually vanishes there. This feature is a direct consequence of vanishing coupling of $a_1$ to $\rho-\pi$. Figure 2 (right) shows the effect of finite pion mass in the vector spectrum. Below $T_c$ one observes the previously mentioned threshold effects
moving downward with increasing temperature. It is remarkable that at $T_c$ the spectrum shows almost no traces of $a_1$-$\rho$-$\pi$ threshold effects. This indicates that at $T_c$ the $a_1$ meson mass nearly equals the $\rho$ meson mass and the $a_1$-$\rho$-$\pi$ coupling almost vanishes even in the presence of explicit chiral symmetry breaking.

In summary, we have presented a detailed study of V-A mixing in the current correlation functions and its evolution with temperature. In the chiral limit the axial-vector 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 $M_{a_1}$. For physical pion mass $m_\pi$, the $a_1$ contribution above $\sqrt{s} \sim M_{a_1}$ still survives although the bump is somewhat reduced. When assuming both dropping $\rho$ and $a_1$ masses, the major change is a systematic downward shift of the vector spectrum [2].

Studying dilepton production in relativistic heavy-ion collisions is an interesting application. The present investigation may be of some relevance for the high temperature and low baryon density scenarios encountered at RHIC and LHC.

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