Hidden Local Symmetry and the Vector Manifestation of Chiral Symmetry in Hot and/or Dense Matter

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The emergence and importance of hidden local symmetry in the structure of hadrons under extreme conditions is discussed. The topics covered are the potentially important role played by an infinite tower of vector mesons encoded in holographic dual QCD in chiral dynamics of mesons and baryons, in the vector dominance and its violation in EW response functions, the presence of the vector manifestation fixed point and its influence on the properties of hadrons in heat bath and in dense matter, the natural emergence of instantons/skyrmions from the pion and infinite tower of vector mesons and their (speculated) role in chiral restoration at high density.

§1. Introduction

In the current understanding of quantum chromodynamics (QCD), nearly all of the masses of low-lying hadrons (e.g., ~98% of the proton mass) come from spontaneous breaking of chiral symmetry. In a glaring departure from molecules, atoms and nuclei whose masses are nearly fully, say, more than 99%, accounted for by their “elementary” constituents, the bulk of the mass of the nucleon is not given by the masses of its constituents, namely, the quarks. This sets the beginning of a series of mysteries related to the question “where does the mass come from?” An intense effort is directed to the issue: How to un-break the broken symmetry and figure out how the mass is generated. I would like to address this issue in this talk using the framework Gerry Brown and I have been developing since some time, based on hidden local symmetry, the “vector manifestation” of chiral symmetry and Brown-Rho scaling.

§2. The origin of hadron mass

We will take the proton as a typical hadron. The argument goes in a similar way for other light-quark hadrons except for the pion. The simplest way is to think of the proton as a bound state of constituent quarks whose masses are dynamically generated from the complex vacuum.

In QCD, the proton is made up of three light (“chiral”) quarks, the total mass of which is only a few MeV, tiny compared with the proton mass ~1000 MeV. The evidence is strong that most of the proton mass comes from the “spontaneous” breaking of chiral symmetry by the vacuum, characterized by the quark condensate \( \langle \bar{q}q \rangle \) as the order parameter. Thus in the chiral limit, one should be able to write the hadron mass as a function of the condensate, as \( m = F(\langle \bar{q}q \rangle) \). When chiral symmetry is restored driven by temperature and/or density to the critical point, the

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order parameter $\langle \bar{q}q \rangle$ will go to zero in various different ways: Either in a smooth way or in a discontinuous way. In either case, the function $F$ must go to zero. However even if the condensate goes to zero smoothly, the $F$ which could be a complicated function of the condensate may go to zero in a discontinuous way. At present, there is no known analytical way to settle this issue using QCD proper. But it seems very natural to expect that $F(\langle \bar{q}q \rangle) \to 0$ as $\langle \bar{q}q \rangle \to 0$. This is basically the basis of Brown-Rho scaling$^1$ and is supported by Harada-Yamawaki’s hidden local symmetry (HLS) theory with the “vector manifestation” (VM) fixed point.$^2$ We will call this Harada-Yamawaki theory “HLS/VM” for short.

We should however caution that this is not the only possibility. In fact, certain models that preserve chiral symmetry and allow a Goldstone-Wigner phase transition can admit a non-zero $F(0)$, hence a non-zero mass. For instance, in a linear sigma model with parity-doublet fermion fields,$^3$ the fermion mass can be non-zero in both the Goldstone and Wigner phases. The fermions can be baryons or constituent quarks. In the former case, one can have massless mesons while having massive baryons at the critical point. In the latter case, both mesons and baryons as (weakly) bound states of quasiquarks could remain massive at the critical point with the chiral symmetry preserved. At present, neither theory nor experiment can rule out this scenario. We shall not pursue this alternative scenario in this talk since our principal theme, HLS, does not admit such a possibility. Experiments will hopefully settle the issue.

§3. Hidden local symmetry

Since the perturbative QCD cannot access the highly nonperturbative and strong-coupling regime at low energy we will be concerned with, we are compelled to resort to effective field theories that meet the criterion of Weinberg’s “folk theorem”$^4$ on effective field theories. The question then is: If the hadron mass vanishes at the phase transition, how can one “see” it, that is, what is the appropriate tool for it?

The principal thesis in this talk is that the most important ingredient in an effective field theory that enables one to probe the regime where the effective mass of the vector meson can drop to that of the pion mass is hidden local symmetry (HLS). Our theme is anchored on the argument by Harada and Yamawaki$^2$ that hidden local symmetry provides a consistent way to allow the vector mass to become as light as the pion mass. We know of no other way to do it. It seems therefore that the lack of hidden gauge symmetry is the reason why the phenomenological models often used in the literature fail to observe dropping masses in hot/dense matter.

3.1. HLS as emergent gauge symmetry

At very low energy $E \ll \Lambda_\chi$ where $\Lambda_\chi \approx 4\pi f_\pi$, the only relevant degrees of freedom are the pions as Goldstone bosons, emerging from the spontaneous breaking of chiral symmetry $SU(N_f)_L \times SU(N_f)_R$ to $SU(N_f)_{L+R}$. The dynamics involving the pion field, $U = \exp(2i\pi/F_\pi)$, is encoded in a chiral Lagrangian expanded in derivatives, the leading term of which is given by low-energy theorems. Now we make the most obvious – and “trivial” – observation that one can always write the
U field in a product form if one introduces a redundant field. Define the L/R chiral fields with the redundant field σ as \( \xi_{L,R} = e^{\mp i\pi/F} e^{i\sigma/F} \) and write \( U = \xi_L^\dagger \xi_R \). In this form, we unearth a local symmetry \( \xi_{L,R} \rightarrow h(x) \xi_{L,R} \) with \( h(x) \in SU(N_f)_V \). Up to this point, we have not done anything, so there is no new physics here. However if we elevate the local symmetry to a local gauge symmetry by introducing a gauge field – which we will denote by \( V_\mu \in SU(N_f)_V \) – and endow it with a kinetic energy term, then it becomes quite a different story. First of all, this procedure allows one to go up systematically in some expansion scheme (such as chiral expansion) in energy from the low energy scale where the pionic chiral Lagrangian is applicable to a scale at which new degrees of freedom set in.\(^5\) This procedure allows one to bypass the breakdown of the pionic chiral theory and go beyond to the next energy scale. In our case, the scale is brought above the mass of the vector mesons \( \rho \), \( \omega \), \( a_1 \) etc. Next thanks to local gauge symmetry, one can do a systematic chiral perturbation calculation with the vector mesons put on the same putting as the pions and access the regime where the vector mass is comparable to the pion mass. One of our chief assertions is that if one wants to study what happens to the vector mesons in medium, this strategy is definitely needed. On a more fundamental level, one can view this as a generic phenomenon of the emergence of local gauge degrees of freedom. Examples are numerous, e.g., emergent gravity, emergent space-time, spin-charge separation in high-T superconductivity etc.\(^6\)

The hidden local symmetry theory of Harada and Yamawaki\(^2\) – which is based on the earlier work of Bando et al.\(^7\) – was constructed in that way with the vector mesons \( \rho \) and \( \omega \) which we will generically label as \( V_1 \) as the hidden local fields together with the Goldstone pions. This strategy of bringing in vector fields as hidden (or emergent) local fields can be extended to higher energies with an infinite tower of vector mesons\(^5\) which can be encapsulated into a five-dimensional Yang-Mills theory as in what is called “dimensionally deconstructed QCD”\(^8\).

3.2. HLS from string theory

A new recent development in both string theory and hadronic physics is that HLS arises naturally from holographic dual QCD based on AdS/CFT duality. This is a top-down approach from string theory to hidden local symmetry theory of QCD. One such theory which astutely implements the spontaneous breaking of chiral \( SU(N_f) \times SU(N_f) \) symmetry was constructed by Sakai and Sugimoto.\(^9\) The key idea in this approach is that the highly non-perturbative aspect of QCD in four dimensions in the limits \( \lambda \equiv g^2_M N_c \rightarrow \infty \) (“’t Hooft limit”) and \( N_c \rightarrow \infty \) can be approximated by a readily calculable weakly-coupled gravity solution in five dimensions. Involving a dimensional reduction, a Kaluza-Klein mass \( M_{KK} \) sets the energy scale of the effective theory. The resulting theory is a pure Yang-Mills theory in five dimensions and is dual to strongly-coupled QCD. When reduced to four dimensions, it contains the pions and an infinite tower of local vector fields coupled gauge invariantly. Thus as in the emergent case, the same type of hidden local symmetry arises from top down. Remarkably this theory describes the meson sector\(^9\) as well as the baryon sector\(^10,11\) quite well.

Perhaps the most important outcome of the development in the context of dense
hadronic matter is the appearance of baryons in the theory. The HLS theory (with the infinite tower of vector mesons denoted as $V_\infty$) is the full theory of hadrons at the scale defined by $M_{KK}$. There are no explicit baryons in the theory and hence baryons must arise through topology, namely, as solitons. In five dimensions, the soliton is an instanton but reduced to four dimensions where the baryon lives, it is a skyrmion. What makes this skyrmion different from the skyrmion in the Skyrme model is that the soliton involves the infinite tower of vector mesons in addition to the pions encapsulated in an instanton with geometry in five dimensions representing the dynamics of the infinite tower of vector mesons. The bulk theory is weak-coupling and manageable in the limit $\lambda \to \infty$ and $N_c \to \infty$ and provides baryon chiral dynamics anchored on hidden gauge structure. One might think that the 't Hooft limit is too stringent a limit for applications to nature. However it has been shown that many aspects of chiral dynamics of baryons could be calculated parameter-free in the 't Hooft and large $N_c$ limit. For instance, for the parameters $\lambda$ and $M_{KK}$ fixed in the meson sector, the axial coupling $g_A$, the nucleon magnetic moments, the vector-meson coupling to nucleons, the EM form factors etc. come out in reasonable agreements with experiments.

At the present stage of our understanding, the holographic approach can make predictions only in the large $\lambda$ and $N_c$ limit, restricted to the zero temperature and matter-free environment. In studying hadron properties in medium, however, it is clear that one has to be able to calculate $1/N_c$ corrections since the hadron masses are locked to the condensates as we argued above and in the large $N_c$ limit, the quark condensate is known to be temperature-independent. At present, one does not know how to compute higher-order $1/N_c$ terms in the bulk sector. Clearly further progress in this direction is needed for physics near the chiral transition point.

§4. Vector manifestation

4.1. HLS à la Harada and Yamawaki

Since one cannot yet adequately exploit the dynamics of the infinite tower in medium, we will therefore rely on the HLS theory of Harada and Yamawaki (HY) which involves the lowest members $\rho$ (and $\omega$) of the infinite tower. Let us call it HLS$_1$ in contrast to the infinite-tower HLS theory of Sakai and Sugimoto which we will call HLS$_\infty$. The HY theory can be interpreted as a truncated version of HLS$_\infty$. One picks the scale $\Lambda_M$ as a matching scale, integrates out all the members of the tower except the lowest member $V_1$ lying below $\Lambda_M$, writes HLS Lagrangian with the $V_1$ and the pion and Wilsonian-matches at $\Lambda_M$ the HLS correlators to the QCD correlators. This gives a bare Lagrangian whose parameters are given by QCD variables such as the strong coupling constant $\alpha_s$, the quark condensate $\langle \bar{q}q \rangle$, the gluon condensate $\langle G_{\mu\nu}^2 \rangle$ etc. Quantum calculations are done with the bare HLS Lagrangian so determined by renormalization group equations. Now since the condensates in the QCD sector are temperature/density dependent, the bare Lagrangian HLS$_1$ is endowed with “intrinsic temperature/density dependence”.

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4.2. The fixed point of HLS\textsubscript{1}

In the chiral limit and with $V_1 = \rho$, there are three parameters in the HLS\textsubscript{1} Lagrangian, $g$, $F_\pi$ and $a$ where $g$ is the gauge coupling constant of HLS\textsubscript{1}, $F_\pi$ is the parametric pion decay constant and $a = (F_\sigma/F_\pi)^2$ figuring in the chiral fields. Harada and Yamawaki showed that the RGE for these parameters have the fixed point consistent with QCD, i.e., $g^* = 0$, $a^* = 1$. This fixed point – “vector manifestation (VM) fixed point” – dictates how the hadronic system makes a phase transition from the chiral symmetry broken phase to the restored phase as the quark condensate vanishes.

In HLS theory, the vector meson masses are generated by the Higgs mechanism, with the scalar $\sigma$ eaten by the vector mesons. The mass formula therefore is $m_V^2 = g^2 F_\sigma^2 = ag^2 F_\pi^2$. Near the critical point, the coupling $g$ goes to zero proportionally to $\langle \bar{q}q \rangle$. Therefore at the chiral restoration, the parametric mass behaves $m_V \sim g \sim \langle \bar{q}q \rangle \rightarrow 0$. The physical mass of $V_1$ also vanishes at the critical point.

4.3. Vector dominance violation

An important consequence of the VM fixed point is that the vector dominance in the EM form factors of hadrons is drastically affected. To see this, consider the pion EM form factor in the HLS\textsubscript{1} theory in which the photon couples to the point-like pion with a coefficient $(1 - a/2)$ and through the $V_1 = \rho$ meson with a coefficient $a/2$. In matter-free space, one has $a \approx 2$, so the form factor is vector-dominated with the direct coupling vanishing. However the point $a = 2$ in free space turns out to be accidental. In fact, $a$ lies on a RG trajectory that does not contain the point $a = 2$. Thus if the system is slightly perturbed from the free space, $a$ quickly flows from 2 toward 1. At the VM fixed point, therefore the vector dominance is strongly violated. This has an important consequence on lepton-pair production in heavy-ion collisions.

§5. “Seeing” the dropping mass

5.1. On-shell probes

There is a flurry of activities, both in theory and experiment, to “see” evidence for the manifestation of chiral symmetry in the behavior of masses and coupling constants in hot and/or dense medium. Among the weakly interacting probes, the most frequently used is the electromagnetic one. There are two classes of processes mediated by the “normal” and “anomalous” components of the chiral Lagrangian:

1. The lepton pair production via virtual photon

$$V \rightarrow \gamma^* \rightarrow l^+ l^-,$$

where $V = \rho$, $\omega$ and $l = e$, $\mu$ is governed by the normal component of the HLS\textsubscript{1} Lagrangian. Most of the past efforts to unravel chiral dynamics of hadrons in medium were directed to this process. See, for updated review, the articles by van Hees and Rapp.\textsuperscript{13)}

2. The other class involves processes that are mediated by the anomalous Wess-
Zumino term in chiral Lagrangians. The process studied in this category\textsuperscript{14}) involves the in-medium $\omega$ meson in

$$\gamma + A \rightarrow \omega + X \rightarrow \pi^0 \gamma + X'.$$  \hfill (5.2)

The coupling $\omega \pi^0 \gamma$ is significant in that it arises from a chiral anomaly and is expected to behave differently in medium from that of the normal process (5.1).

5.2. \textit{Off-shell probes}

There are indirect probes that indicate how hadron masses and coupling constants behave in dense medium. A recent discussion on this matter can be found in the review by Brown et al.\textsuperscript{15}) Most of the relevant arguments given there have been developed in a series of articles that date way back to early 1990's.\textsuperscript{16}) What transpires from these studies is that the manifestation of chiral symmetry in medium – which is necessarily present – is compounded with mundane nuclear many-body processes and cannot be unambiguously isolated at ordinary nuclear matter density. This applies to all processes, including heavy ions, that sample predominantly the density regime near the nuclear saturation density.

5.3. \textit{What the dileptons see}

Experimentalists in heavy ion physics purport to extract an in-medium “spectral function” of a vector meson quantum number as a function of invariant mass. An “ideal” snapshot for this is thought to be the dileptons mentioned above. In order to expose the effect of dense and/or hot medium, one tries to subtract all possible “trivial effects” that take place in zero-temperature, zero-density environment (e.g., “cocktail events”). Whether this can be done in a fully consistent way is not clear. Let us suppose for the sake of discussion that all such trivial effects can be taken out of the given experimental results and theorists are given what may be called “IMESF” (in-medium experimental spectral function). The question is: \textit{Can the IMESF so obtained be used to verify or falsify Brown-Rho scaling or the vector manifestation scenario?}

To properly answer this question, it would be necessary to have at one’s disposal one complete self-consistent theoretical framework in which all the calculations for all processes involved can be done. Furthermore the spectral function should be expressed in terms of variables that can track the chiral property of the system in terms of the relevant order parameter. HLS\textsubscript{1} theory provides one such framework.

The theoretical ingredients necessary within the framework of HY’s HLS\textsubscript{1} theory were spelled out in two articles.\textsuperscript{17}) They are (1) the intrinsic background (temperature, density) dependence (IBD) demanded by matching to QCD,\textsuperscript{2}) (2) the violation of the vector dominance in the pion EM form factor in hot and/or dense medium that results from the vector manifestation of chiral symmetry in the HLS/VM theory\textsuperscript{18}) and (3) many-body correlations generated by the presence of the Fermi surface, which may be considered as a quantum critical phenomenon.\textsuperscript{15})

In order to implement all three ingredients in a consistent way, baryonic degrees of freedom are mandatory. In HLS\textsubscript{\infty} theory, they are skyrmions in an infinite tower of vector mesons if viewed in four dimensions. No such formulation exists at the
moment. We shall just assume that we have a spectral function calculated in that formulation and call it “TSF” (theoretical spectral function). Unfortunately, having such a TSF is not enough to meaningfully confront the IMESF. One also has to know the conditions with which the measurement of the IMESF is made. The experiment typically involves summing over the dilepton emissions as the system evolves in temperature and density as it expands. Many subtle effects, such as for instance the “memory effects” pointed out in Ref. 19), will have to be all taken into account. Given the formidable and complicated nature of the requirements, it is not clear that the theorists have the full control on these.

Up to date, the only spectral function computed in HLS/VM is the one calculated by Harada and Sasaki\(^{20}\) in which only the temperature effects in the ingredients (1) and (2) were taken into account. Incomplete as it is, the Harada-Sasaki spectral function cannot be directly compared with the experimental data. Nonetheless what Harada and Sasaki found\(^{20}\) is quite illuminating. First of all, mass shifts in the TSF cannot occur without the intrinsic background dependence (IBD) taken into account. Next as a consequence of the IBD, a finite temperature and density make the VD violated, maximally at the VM fixed point. The spectrum of the emitted lepton pairs will be appreciably modified from that given by the vector dominance. Measured by the lepton pairs that come from both the direct pions and the vector mesons, the width will be smeared while the (pole) strength will be cut down by a factor \(\lesssim 4\). Since the chiral restoration effect is operative only above the “flash temperature” and “flash density”,\(^{16}\) the dileptons emitted with the imprint of chiral restoration will be highly diluted, if not totally swamped, by the dileptons coming from near on-shell.

Although we are unable to compare directly what is predicted by HLS/VM to data, we can however answer the question posed at the beginning of this subsection in the negative. A corollary to that answer is that the result obtained in the analyses of\(^{13}\) – that mundane strong hadronic interactions can adequately explain the available dilepton data – cannot be taken as an evidence that the HLS/VM scenario is invalidated or “ruled out”. It merely indicates that the relevant signals are masked by the mundane processes that have nothing direct to do – though consistent\(^{21}\) – with chiral symmetry.

5.4. The Wess-Zumino-term induced process

In the SS theory of holographic QCD, the process (5.2) mediated by the Chern-Simons action is vector-dominated as \(\omega \rightarrow \pi^0\bar{\rho} \rightarrow \pi^0\gamma^*\) where \(\bar{\rho} = \rho, \rho', \ldots\). Furthermore the analysis in Ref. 2) showed that there is no direct coupling in the \(\omega \rightarrow \pi^0\gamma\) decay even in the HLS\(_1\) theory. We can therefore ignore the direct coupling. This makes the process quite neat and simple as all anomaly-mediated processes are. As far as we know, no analysis using the Wess-Zumino structure of the process has been made yet. It would be interesting to analyze the CBELSA/TAPS experiment taking into account the anomaly structure present in the HLS framework.
§6. Dense matter and half-skyrmions

Hadronic physics at high density relevant to the interior of compact stars is poorly understood at present. Given the paucity of model-independent tools, we can be allowed to speculate on an intriguing, hitherto unexplored, phase structure at high density based on the instanton/skyrmion structure of the baryon inherited from holography.

A novel structure observed in the study of dense baryonic matter at high density in terms of Skyrme crystals\textsuperscript{22)} implied that a skyrmion fractionizes at a certain density $n_{\text{meron}} > n_0$ into two half-skyrmions. In HLS$_\infty$ theory, the skyrmion-half-skyrmion transition can be interpreted as an instanton-meron transition in a close analogy to the magnetic Néel-VBS transition in condensed matter where the appearance of the merons as relevant degrees of freedom is interpreted as a quantum deconfinement phenomenon.\textsuperscript{23)} One of the most important consequences of the existence of such a phase could be that the normal matter that is unstable against Cooper pairing and goes over to color superconductivity at high density could be a non-Fermi liquid state. That would make color superconductivity similar to high-$T_c$ superconductivity.

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