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MEDIUM DEPENDENCE OF THE VECTOR-MESON MASS: DYNAMICAL AND/OR BROWN–RHO SCALING?*

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We discuss the similarities and differences for the theories of Rapp, Wambach and collaborators (called R/W in short) and those based on Brown–Rho scaling (called B/R), as applied to reproduce the dileptons measured by the CERES collaboration in the CERN experiments. In both theories the large number of dileptons at invariant masses $\sim m_\rho/2$ are shown to be chiefly produced by a density-dependent ρ-meson mass. In R/W the medium dependence is dynamically calculated using hadronic variables defined in the matter-free vacuum. In B/R scaling it follows from movement towards chiral symmetry restoration due to medium-induced vacuum change, and is described in terms of constituent (or quasiparticle) quarks. We argue that the R/W description should be reliable up to densities somewhat beyond nuclear density, where hadrons are the effective variables. At higher density there should be a crossover to constituent quarks as effective variables scaling according to B/R. In the crossover region, the two descriptions must be "dual." For the moment there is a factor $\gtrsim 2$ difference between the predicted number of dileptons from the two theories,

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B/R scaling giving the larger number. We show that a substantial factor results because in B/R, fluctuation is made about the "vacuum" modified by density, so that a different mass m_ρ^* appears in the Lagrangian for each density, thereby rendering residual interactions between hadrons weaker, whereas R/W calculate a mass m_ρ^* for each density with an effective Lagrangian defined in the zero-density vacuum, which has the free m_ρ in the Lagrangian and hence the coupling is strong. Thus more diagrams need to be incorporated in R/W to reduce the discrepancy. On the other hand, R/W include processes which may be additional to these of B/R. These constitute several (smaller) corrections. It is argued that the N^*-hole state $[N^*(1520)N^{-1}]^{1^-}$ is almost completely ρ-meson like in content; *i.e.*, it is, to a good approximation, just the state $\rho|0\rangle$ that would be produced by the ρ-meson field acting on the nuclear ground state (finite temperatures are not expected to disturb this picture by much).

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1. Introduction

Relativistic heavy-ion collisions carried out at the CERN-SpS by the CERES collaboration [1] show an excess of dileptons in the mass region below the vector meson mass m_ρ. For dilepton invariant masses of $\sim m_\rho/2$, the enhancement is an order-of-magnitude over conventional theories which do not have a medium-dependent ρ-meson mass. In fact, roughly speaking, the ρ-meson must have an in-medium mass of $\sim m_\rho/2$ for a sufficient time in the heavy-ion collision to be able to produce the enhanced number of dileptons of invariant mass $\sim m_\rho/2$. Such times are provided in current transport calculations of the CERN experiments.

We argue in the following that this can be accomplished in the meson sector by a dynamical lowering of the ρ-meson mass produced by coupling to N^*-hole states, especially the $[N^*(1520)N^{-1}]^{1^-}$. This is an important ingredient in the R/W theory [2] which makes it possible to approximately describe the number of dileptons in the mass region $\sim m_\rho/2$. The R/W theory posits hadrons with free masses as the appropriate variables. This must be reliable at low density. But at high density, the R/W theory will become strong-coupling necessitating the consideration of a large number of diagrams. It is then more advantageous to go over to a medium-modified "vacuum" around which fluctuations into various flavor directions can be treated in a weak-coupling approximation. This is the basis of the quasi-particle picture associated with B/R scaling [3, 4], suggested also by QCD sum-rule calculations [5, 6].

Although we use the shorthand notation for this state $[N^*(1520)N^{-1}]^{1^-}$, it is a highly collective state, in which each of the N nucleons is excited, with coefficient $1/\sqrt{N}$, to the N^* at energy 1520 MeV. Since the 580 MeV excitation energy ([1520-940] MeV) is large compared with the temperatures encountered in heavy-ion collisions, the collective state is relatively unaffected by temperature. In the hot fireball many excitations of nucleons such as the $\Delta(1232)$ isobar will be present. We argue that, in analogy with nuclear structure, these excited states of the nucleons should have dipole excitations at not very different relative energies from that of the dipole excitation built on the ground state. By retaining only nucleons, as Rapp and Wambach have done, we underestimate the dynamical change in the ρ-meson mass. This should be kept in mind when considering central heavy-ion collisions where their present theory seems to underestimate the experimental data. Inclusions of the dipole excitations built on nucleon excited states would substantially increase their predicted dilepton yield. An upper limit to this effect (R/W now have a lower limit) would be obtained by using the total baryon density rather than that of just the nucleons, as they have done.

Brown, Buballa and Rho [7] showed that the chiral phase transition could be sensibly made only if the relevant variables close to the transition were constituent quarks, the chiral restoration being accomplished in terms of the quarks going massless in the chiral limit. On the other hand, nuclear matter is more economically described in terms of hadron variables to describe saturation although hybrid descriptions in terms of hadron-quark-bags and hadrons with B/R scaling can be constructed to work [8]. Somewhere between nuclear matter density and that of chiral restoration, the effective variables will smoothly change from hadronic to constituent quarks subject to B/R scaling. (This change over was not, however, constructed by Brown, Buballa and Rho.) This construction of the phase transition suggests that the Rapp/Wambach description should hold for densities up to and somewhat beyond nuclear matter densities, with hadrons as the relevant variables, but give way to that from Brown/Rho scaling at the higher densities. Near the hadron-quark changeover, the two descriptions must be "dual" to each other in a way analogous to quark-hadron duality in heavy-light-meson systems [9]. In this description, the dynamical lowering obtained by R/W may give way at higher density to the B/R scaling dictated by chiral (and scale) symmetry before reaching the chiral restoration transition.

The dilepton production, which is the only way we presently have of mapping out the m_ρ^* as function of density, should be insensitive to the density at which this crossover is made, and we suggest how this can be realized in practice.

In this note we deal only with the density dependence in the ρ meson-mass. However, symmetries in (constituent) quasiquarks are expected to give a similar scaling for the ω as well as other light-quark hadrons. Work on this will be deferred to a future investigation.

It should be mentioned that there is evidence for this "dual" description at density up to that of normal nuclear matter. It was shown in [8, 10] that the B/R scaling parameter (denoted as Φ) is related by Landau Fermi-liquid theory to the Landau quasiparticle interaction constant F_1. This connection is a statement on a possible relation at low energy/density between the vacuum structure characterized by the quark condensate and the nuclear interactions characterized by Landau Fermi-liquid parameters. The upshot of the present paper is that beyond nuclear matter density up to the chiral phase transition, Fermi liquid theory of quasiquarks may become more appropriate. Such phenomena as color superconductivity and flavor-color locking discussed recently [11] could be treated more realistically starting from the Fermi liquid theory of quasiquarks.

2. Dynamical mass scaling

Most interesting for the dynamical effects are the invariant mass distributions at small and large $p_\perp$ of electron pairs. Since the CERES acceptance is basically central rapidity, $p_\perp \simeq p$, the total momentum, so that the energy p_0 of an electron pair is essentially

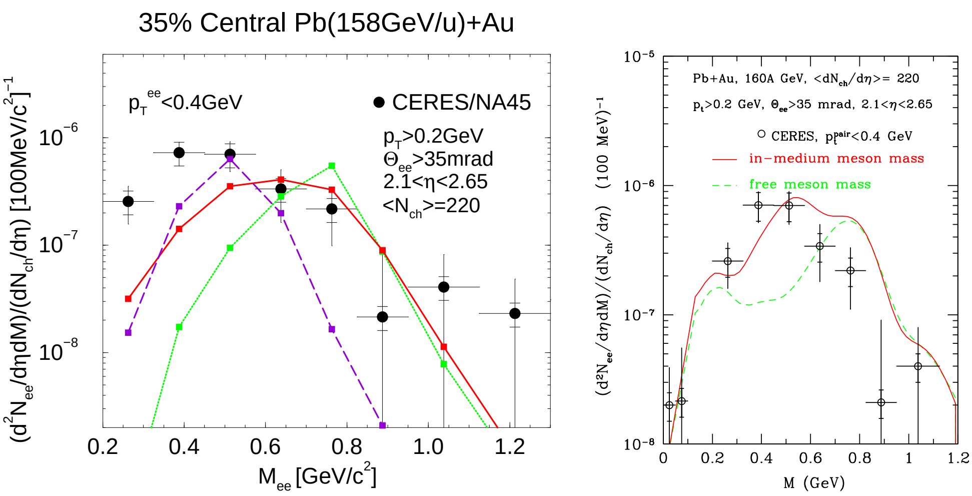
$$p_0 \simeq \sqrt{(m_\rho^*)^2 + p_\perp^2} \tag{1}$$

with m_ρ^* the effective mass of the vector mesons ρ or ω. Experimentally it turned out that the low $p_\perp$ region is highly enhanced, by a factor ~ 10, whereas the high $p_\perp$ region seems to exhibit a much smaller enhancement [12]. This is completely opposite to Fig. 7 of Friman and Pirner [13]. Since the Friman–Pirner paper it has been realized that the cutoff in the form factor used by these authors ($\Lambda_{\rho N^* N}$=1.5 GeV) is too large. Thus the P-wave coupling to N^* resonances was overestimated. Similar conclusions were reached by Friman for the πNN form factor [14] (which is related to medium effects in the pion cloud of the ρ), which can be severely constrained from the analysis of $\pi N \to \rho N$ data.

An important paper by Lee [15] shows that from QCD sum rule calculations the vector meson mass, broken down into scalar and momentum-dependent components, is for the ρ-meson

$$\frac{m_\rho(n_n)}{m_\rho(0)} = 1 - (0.16 \pm 0.06)\frac{n_n}{n_0} - (0.014 \pm 0.005)\left(\frac{\vec{q}}{0.5}\right)^2 \frac{n_n}{n_0}\,, \tag{2}$$

where $|\vec{q}|$ is in GeV and n_0 is the nuclear saturation density. Thus, the scalar term, which he interprets as Brown/Rho scaling, is large, whereas the $\vec{q}^2$ term, which could arise from P-wave coupling of the ρ to isobars



(a) (b)

Fig. 1. Dilepton mass spectra with $p_t^{\text{pair}} < 0.4$ GeV in Pb+Au collisions at 158 GeV/u compared with: (a) fireball calculations by R. Rapp (left panel) using the R/W spectral function (full curve), B/R scaling (dashed curve) and without medium effects (dotted curve); Dalitz decay contributions are not included here; (b) transport calculations by G.Q. Li (right panel) using B/R scaling (full curve) and without medium effects (dashed curve).

and from relativistic corrections to S-wave couplings, is small. This is in agreement with the $p_\perp$-distribution. Rapp's calculation for $p_\perp < 0.4$ GeV/c, compared with the experimental points is shown in the left panel of Fig. 1 (Dalitz pairs are not included here). We shall concentrate on the energy region around $M_{ee} = m_\rho/2$. This is sensibly above the π^0 background peak, and yet low enough to make it impossible for theories without dropping ρ-mass to achieve the observed enhancement. It should be noted that the Rapp curve is a factor ~ 2 below the experimental points. Note also that the curve with *no* medium effects in the ρ-mass lies an order-of-magnitude below the data.

The near agreement of the current Rapp/Wambach calculations with the empirical $p_\perp < 400$ MeV/c-spectrum shows in terms of Eq. (2) that their $\vec{q}^{\,2}$ term is rather small compared with the effective mass term (corresponding to the second term on the RHS of Eq. (2)). So, directly from the inspection of this curve we can see that they have a rather small m_ρ^* at the relevant densities. In the right panel of Fig. 1 are shown results calculated by G.Q. Li using the Li–Ko–Brown theory [4]. Here, the Dalitz pairs are included. The free meson mass curve is shown to be still a large factor, ~ 5 too low. The curve with in-medium meson masses is similar in shape to that of Rapp, but a factor $\simeq 2$ higher than his curve. In Fig. 2 the $p_\perp$ distribution from Li–Ko–Brown theory is shown to generally provide a good fit.

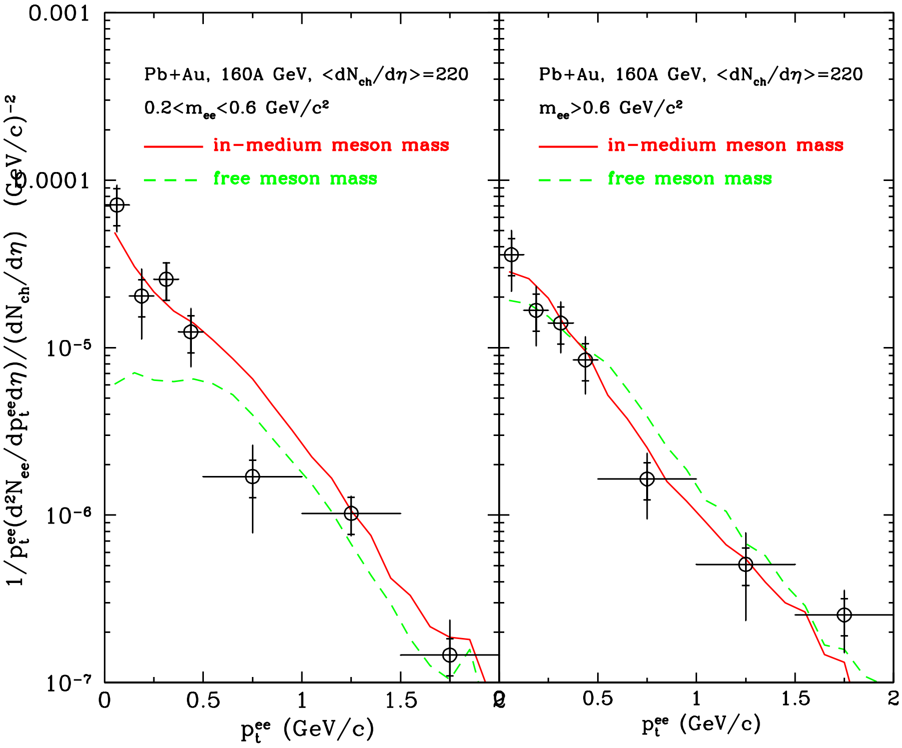


Fig. 2. Dilepton p_t spectra in two invariant mass bins in Pb+Au collisions at 158 AGeV compared with the transport calculations by G.Q. Li using B/R scaling (full curves) and without medium effects (dashed curves).

In the following we show a crucial ingredient in the Rapp/Wambach dilepton enhancement is a dynamical lowering of the ρ-meson mass, accomplished by S-wave interactions coupling to N^*-hole states.

Rapp *et al.* [16] in preparation for including scalar isobar excitations in the dilepton analysis, have calculated photoabsorption cross sections on protons and nuclei. The (with respect to dilepton production) most important excitation is that of the $N^*(1520)$, the other S-wave excitations being smaller. In the present R/W theory the latter may make up an $\sim 30\%$ correction to that from the $N^*(1520)$. However, we believe that only the latter should be multiplied by the full baryon — rather than nucleon — density, since the dipole excitations can be built upon excited nucleon states. Thus, the importance of the $N^*(1520)$ in their theory, compared with the non-collective excitations, should be greater. Using a phenomenological Lagrangian of the form [16, 17]

$$\mathcal{L}^{\text{s-wave}}_{\rho N^* N} = \frac{f_{\rho N^* N}}{m_\rho} \Psi^\dagger_{N^*} \; (q_0 \; \vec{s} \cdot \vec{\rho}_a - \rho^0_a \; \vec{s} \cdot \vec{q}) \; t_a \; \Psi_N \; + \; h.c. \tag{3}$$

they determine

$$f^2_{\rho N^* N}/4\pi = 5.5 \tag{4}$$

from fits to the photoexcitation data. In addition to the $\Gamma_0 \simeq 120$ MeV natural width of the $N^*(1520)$ they include an additional medium dependent width of 250 MeV for nuclear matter density.

Rapp *et al.* diagonalize the interactions leading to several N^* resonances. Here we make a schematic calculation of the excitation of the $N^*(1520)$, which gives the dominant contribution. Consider the two-level toy model of the $N^*(1520)$ and the ρ. The two branches in the ρ spectral function can be located by solving the (real part of) the ρ-meson dispersion relation (at $\vec{q} = 0$),

$$q_0^2 = m_\rho^2 + \text{Re}\Sigma_{\rho N^* N}(q_0) \; , \tag{5}$$

self-consistently. Including also the backward-going graph the $N^*(1520)N^{-1}$ excitation contributes to the self-energy at nuclear matter density n_0

$$\Sigma_{\rho N^* N}(q_0) = f^2_{\rho N^* N} \; \frac{8}{3} \; \frac{q_0^2}{(m_\rho)^2} \; \frac{n_0}{4} \; \left(\frac{(\Delta E)^2}{(q_0 + i\Gamma_{\text{tot}}/2)^2 - (\Delta E)^2} \right) , \tag{6}$$

where $\Delta E \approx 1520 - 940 = 580$ MeV and $\Gamma_{\text{tot}} = \Gamma_0 + \Gamma_{\text{med}}$ is the total width of the $N^*(1520)$. When neglecting any in-medium corrections to the width of the $N^*(1520)$ we find two solutions for Eq. (5), located at

$$q_0^- \simeq 540\text{MeV} \quad , \quad q_0^+ \simeq 895\text{MeV} \; . \tag{7}$$

Solving Eq. (5) is in fact equivalent to determining the zeros in the real part of the ρ-meson propagator,

$$D_\rho(q_0, q) = 1 \Big/ \left[q_0^2 - q^2 - m_\rho^2 - \Sigma_{\rho N^* N}(q_0, q) + i m_\rho \Gamma_\rho \right] \tag{8}$$

at vanishing 3-momentum (*cp.* long-dashed line in the lower left panel of Fig. 3). However, it is more instructive to examine the imaginary part of D_ρ which is directly related to the ρ-meson spectral function $A_\rho = -2\text{Im}\ D_\rho$. For Γ_{med}=0 we clearly see the two states corresponding to the two solutions quoted above (long-dashed line in the upper left panel of Fig. 3), with the low-lying peak actually situated at q_0 =500 MeV. Although for finite Γ_{med} the low-lying solution disappears (short-dashed line in the lower left panel of Fig. 3), the ρ-spectral function still exhibits appreciable strength around $q_0 \simeq 550$ MeV, *i.e.* the low-lying state simply broadens thereby losing some of its collectivity (short-dashed curve in the upper left panel of Fig. 3). However, only a fraction of the ρ-meson strength resides in this lower state ($Z_- \simeq 0.2$). This constitutes a significant difference from B/R scaling in

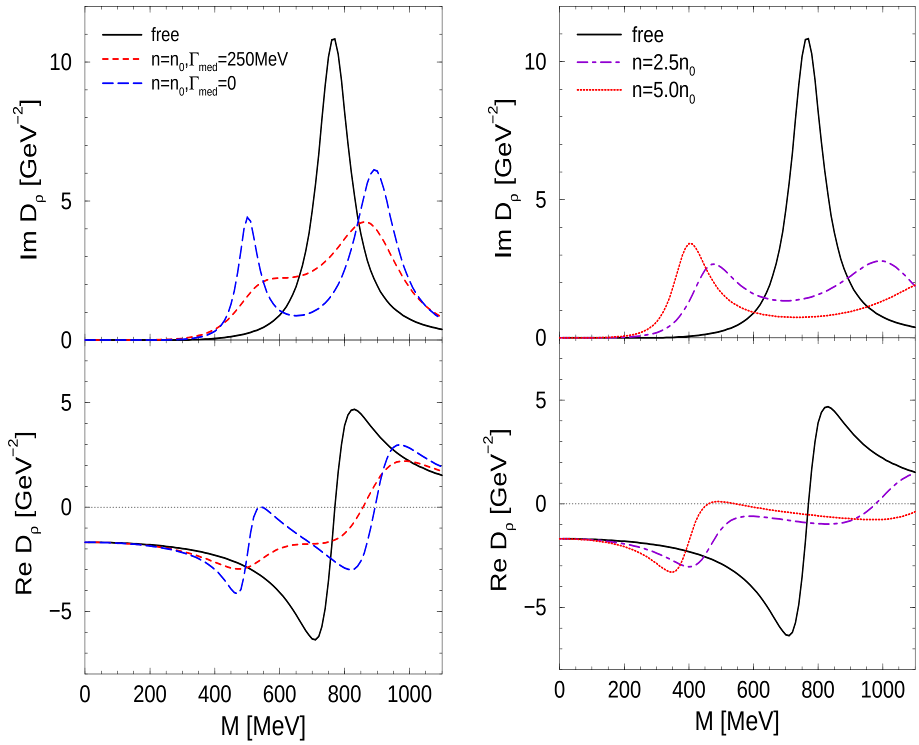


Fig. 3. Real part (lower panels) and imaginary part (=spectral function, upper panels) of the ρ-meson propagator when including $N^*(1520)N^{-1}$ excitations according to Eq. (6); left panel: at n=0 (full curves) and at normal nuclear matter density (n=n_0) for two different values of the in-medium $N^*(1520)$ width, namely $\Gamma_{\rm med}$=0 (long-dashed curves) and $\Gamma_{\rm med}$=250 MeV (short-dashed curves); right panel: development of the collective state at higher nuclear densities, *i.e.* n=2.5n_0 (dashed-dotted curve) and n=5n_0 (dotted curve), both for $\Gamma_{\rm med}$=250 MeV.

which the scalar meson field brings the m_ρ^* down to $m_\rho/2$ for $n \simeq n_0$, but leaves the full pole strength. Although R/W lose dileptons, as compared with B/R scaling, they include many other channels such as further scalar excitations *etc.* This leads to a final discrepancy of a factor $\sim$2 as can be roughly inferred from the peak in the $p_\perp < 400$ MeV/c M-spectrum of Rapp in Fig. 1, which is about half of that of the calculation using B/R scaling.

However, the R/W peak will be substantially increased if the full baryon density is used in calculating effects of the $N^*(1520)$, and the relative role of the other effects will be smaller (note that their use of nucleon — rather than baryon — density is probably more correct for the non-collective S-wave resonances).

3. Collective modes more generally

Nuclear giant resonances are often produced by operating on the "vacuum"(*i.e.*, nucleus in its ground state) by the appropriate operator. Thus, the giant dipole state (GDR) is typically constructed as

$$\Psi(\mathrm{GDR}) \simeq D\Psi_0 \ , \tag{9}$$

where $D = N\sum z_i\tau_i$ with N the normalization constant. $\Psi(\mathrm{GDR})$ is a coherent sum over particle-hole excitations.

In a similar way, the collective N^*-hole state with quantum numbers of the ρ-meson is

$$\Psi_\rho = \rho|0\rangle \simeq [N^*(1520)N^{-1}]^{1^-} \ , \tag{10}$$

since each N^*-hole excitation has the same energy. In fact $N^*(1520)$ decays $\sim 80\%$ of the time by π or 2π emission, and the dispersion from this decay lowers its energy by 190 MeV, cutting down the decay into the ρ-channel by the factor

$$F = \frac{(\Gamma_\rho/2)^2}{(190\mathrm{MeV})^2 + (\Gamma_\rho/2)^2} = \frac{1}{7.4} \tag{11}$$

from what the decay to the ρ would be were the $N^*(1520)N^{-1}$ at the ρ-pole. There is an additional factor of $3/8$ for the proportion of the direct product $N^*(1520)N^{-1}$ which is coupled to $J^P = 1^-$. Thus, the internal structure of $[N^*(1520)N^{-1}]^{1^-}$ is estimated to have fraction

$$f > \frac{7.4\times 8/3\times 0.2}{0.8 + 7.4\times 8/3\times 0.2} = 0.83 \ , \tag{12}$$

where the 0.8 in the denominator is the observed fraction of $N^*(1520)$ decay into $N\pi$ or $N\pi\pi$. The f is greater in (12) because lowering the energy of the $N^*(1520)N^{-1}$ state from that of the ρ will decrease the pion decay. Our conclusion is that the $[N^*(1520)N^{-1}]^{1^-}$ is about as close to $\rho|0\rangle$ as the $D\Psi_0$ is to the $\Psi(\mathrm{GDR})$ eigenstate. The difference is that the elementary particle corresponding to the GDR is the photon, whose zero mass is protected by gauge invariance whereas here the nonabelian gauge particle (*i.e.*, ρ) is massive (which may be considered as due to Higgs mechanism a la spontaneously broken hidden gauge symmetry).

One might ask why the $N^*(1520)N^{-1}$ comes at an energy 190 MeV below that of a free ρ. It is easy to see that the open π and 2π decay channels have dispersion corrections which move the energy of the $N^*(1520)N^{-1}$ down. Taking these to come from loop corrections involving the off-shell decay of the ρ, one sees that there is a certain self-stability, in that if the $N^*(1520)$ drops too far in energy, the pion decay will be cut off. The detailed evaluation of the dispersion correction remains to be done, however.

Consequently, in the case of the ρ-meson, the elementary ρ and the nuclear collective state $\rho|0\rangle = \sum[N^*(1520)N^{-1}]^{1^-}$ will interact strongly, the symmetrical contribution moving to energy $\sim m_\rho/2$. The baryons, neutron and proton, have isospin degeneracy 2, so one can build up two nuclear vector mesons. The coupling between elementary ρ and N^*-nucleon-hole ρ should be universal.

4. Broadening

One of the chief differences between R/W theory and that following from B/R scaling is that the ρ-meson is very broad in the former whereas Li, Ko and Brown [4] worked in mean field approximation. Ko [18] has added effects of collision broadening to the latter theory. In lowest order the effects such as π-ρ scattering give a large width in the denominator of the ρ-propagator because the lifetime of the wave packet representing the ρ is terminated by such a collision. The short lifetime is accompanied by a large width. Thus, the contribution from lowest order is substantially reduced, due to the large $\Gamma_{\rm med}$. However, in next order the dilepton production from the π-ρ interaction adds to the numerator, compensating for the decrease due to the introduction of the large $\Gamma_{\rm med}$ in lowest order. To the extent that the additional terms added to the numerator compensate for the width in the denominator, the broadening therefore does not change the situation.

5. Conclusion

We have shown that a large contribution to the low-mass dilepton spectrum in the R/W scenario comes from the elementary ρ mixing with the $[N^*(1520)N^{-1}]^{1^-}$ state. This produces a strong elementary ρ component at an energy $\sim m_\rho/2$ for nuclear matter density n_0.

The $[N^*(1520)N^{-1}]^{1^-}$ has as main component the giant resonance $\rho|0\rangle$. In this sense it is analogous to the particle-hole combination of the giant dipole resonance in nuclear theory, $\Psi(\mathrm{GDR}) = D|0\rangle$, where D is the dipole operator and $|0\rangle$ the ground state of the nucleus. Thus, the $[N^*(1520)N^{-1}]^{1^-}$ is chiefly a coherent state of N^*-hole combinations, summed over all nucleonholes, with the quantum numbers of the ρ-meson. Many other small components of the in-medium ρ also contribute in R/W.

An important ingredient in the R/W calculations leading to low-mass dilepton enhancement is the low-mass component of the ρ at around 500 MeV for nuclear matter density n_0 (this component has, however, a strength of only $\sim$ 20% of the bare ρ, although many other components are mixed through the spectra).

Moving to higher densities/temperatures we claim that the full baryon density n_B should be used in calculating $\Sigma_{\rho N^* N}$, because excited baryons will also have a dipole state built on them. This may not have quite the same regularity as the dipole state built on the nucleons. Also finite temperature effects may enter. Thus we expect to somewhat overestimate the rate at which the symmetric coherent state moves down in energy. From m_ρ^* =550 MeV at nuclear matter density this state moves down further with density. At baryon densities of around $5n_0$, which roughly correspond to initial conditions in central 160GeV/u Pb+Au, it has reached about 400 MeV (see right panel of Fig. 3). This seems not enough to provide a direct link to B/R scaling, and can be traced back to the fact that the preservance of gauge invariance at the hadronic level requires derivative coupling of the ρ to the nucleons (resulting in the q_0^2-factor in Eq. (6), which slows down the rate of decrease in mass appreciably). This feature is not present in the B/R scenario (in which the factor q_0^2/m_ρ^2 in Eq. (6) would be replaced by unity), which, however, is chiefly designed to work at the constituent quark level. Working with constituent quark degrees of freedom, Brown, Buballa and Rho found the phase transition to occur around $n_c = 2.75\rho_0$ [7], *i.e.* the ρ-meson becoming massless at this point. To the extent that this results, the changeover from hadronic to constituent quark language should be made rather early for densities not very far above n_0. Below n_0 the hadronic language should certainly be used. In this sense, the question may be no longer which is the 'correct' scenario, but at precisely what densities does the hadronic description break down. This may in fact be studied experimentally in terms of systematic centrality dependencies in the dilepton yield in a quantitative way. The explicit demonstration of quark-hadron duality in this context, which has to show up in some intermediate density regime, remains a theoretical challenge.

Whereas the first author, in writing this paper, has extolled the virtues of B/R scaling, it should be recognized that R/W have provided us with close connections with many observable phenomena in the hadronic world. We have learned that form factors of P-wave couplings must be drastically softened, firstly in order to reproduce known two-body collision data [14], but generally so as to make the $\vec{q}^{\,2}$ term in Eq. (2) small, essentially unimportant. The analysis [16] found the $f_{\rho N^* N}$ to the $N^*(1520)$ resonance to be very close to that we find from universal vector meson coupling. In general, it has been useful to give new and improved understanding of the many empirical processes which figure in the R/W description. It is highly satisfying that R/W and B/R end up in qualitative agreement[1]. It is remarkable that what started out to be a highly complicated dynamical mechanism in R/W might turn out to have an extremely simple picture in terms of weakly interacting quasiparticles. This then provides evidence for correspondence between the hadronic picture and the partonic (quasiparticle) picture in the high density regime comparable in quality to what one gets at nuclear matter density when probed by very low energy electroweak probes, such as static moments of heavy nuclei, nuclear axial-charge transitions and nuclear matter properties [8]. One plausible way of making the crossover from the low to high density regime would be to shift from *nuclear* Fermi liquid structure to *quasiquark* Fermi liquid, with the collective state in the ρ-meson channel constructed above being an analog to zero-sound excitation on top of the Fermi liquid ground state defined at a given density.

Furthermore, B/R suggested their scaling as only approximate. It is essentially an effective theory treated at tree order. Some of the effects taken into account in R/W may not be included in B/R and vice versa. Considering other mesons such as the $\omega(783)$ we should be able to calculate differences in scaling, that is, corrections to the tree order results (note, *e.g.*, that Lee [15] has a much greater momentum dependence in m^*_ω than in m^*_ρ). We have also been able to identify many other baryon resonances in the particle data tables which are likely to be dipole excitations on lower-mass resonances. We believe that what we have learned here will be very useful in calculating the deviation from B/R scaling.

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