Medium Modification of Hadrons

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Abstract. The theory of the strong interaction, Quantum Chromodynamics, has been remarkably successful in describing high-energy and short-distance-scale experiments involving quarks and gluons. However, applying QCD to low energy and large-distance-scale experiments has been a major challenge. Chiral symmetry is one of the most fundamental symmetries in QCD and provides guiding principles to deal with strong interaction phenomena in the non-perturbative domain. Various QCD-inspired models predict a modification of the properties of hadrons in nuclear matter from their free-space values. A review of experiments searching for the in-medium modifications of light mesons and baryons will be given trying to assess if they confirm or refute these theoretical predictions.

Keywords: Medium modifications, mesons, di-lepton decay.

INTRODUCTION

In the current picture, ordinary matter represents only 4% of the total energy content of the universe and is made of leptons, quarks, and the particles that bind them. Hadrons, the strongly interacting particles are composite objects made of quarks and gluons. The dynamics of quarks and gluons is described by Quantum Chromodynamics (QCD) and manifests very peculiar properties. For most composite systems, the total mass of the system is close to the sum of the masses of the constituents. However this is not the case for nucleons. The masses of the u and d quarks are less than 10 MeV so naively one might expect the mass of the nucleon m\(_{\text{nuc}}\)~20-50 MeV. However, the observed mass of the nucleon is of the order of 1000 MeV. The QCD vacuum is modified by the spontaneous breaking of chiral symmetry giving the u and d quarks in the nucleon an "effective" mass of some 300 MeV/c\(^2\). The Higgs mechanism is only responsible for ~2% of the mass of the nucleon, QCD dynamically generates the remaining 98% of the mass. Many experiments are carried out at different laboratories looking at the properties of hadrons and trying to describe them in terms of the fundamental degrees of freedom of QCD (quarks and gluons). This latter approach is successful at high energies/small distances but is still problematic at low energies/large distances. At low energies, standard nuclear physics with nucleon and meson degrees of freedom work effectively in describing observations. The transition between the two descriptions of hadrons is one of the main goals of hadronic physics. Lattice QCD calculations have made tremendous progress and will one day give us a full description of strong interactions under all regimes. Meanwhile, effective theories incorporating some of the main features of QCD have been successfully developed and help us gain insight into the non-perturbative regime of QCD. The study of the properties of hadrons in the medium provides stringent tests for these different models.

CHIRAL SYMMETRY BREAKING

In QCD, the fundamental fields are the quarks and gluons, and their dynamics are described by the QCD Lagrangian. This lagrangian exhibits a number of interesting properties. The most remarkable being that for an essentially “parameter free theory” it can account for the rich phenomenology of hadronic and nuclear physics. A simple approximation is to set the masses of the light quarks u, d and s to zero and those of the heavy quarks c, b and t to be infinite then the only parameter left in the QCD lagrangian is the running coupling constant g which is a
function of the scale at which it is measured. At low energies (large distances) the coupling constant is large but it decreases with increasing energy (short distances), this is the famous phenomenon of asymptotic freedom.

Other important features of the QCD lagrangian are its symmetries. If we assume that the quark masses are equal to zero, then the flavor symmetry is enlarged. Left and right-handed quark fields do not couple to each other. This corresponds to Chiral Symmetry and it is one the fundamental symmetries of QCD in the limit of massless quarks. Under this symmetry, chiral partners (pseudo-scalar-scalar, vector-axial) are expected to be degenerate in mass. In reality the quarks have non-zero masses and chiral symmetry is explicitly violated. However, if we restrict ourselves to only u and d quarks, ($m_u, m_d < 10$ MeV) their relatively small masses can be neglected leading to an approximate chiral symmetry. Even if the QCD lagrangian is chiral invariant, the ground state (QCD vacuum) at zero temperature and density violates chiral symmetry. Chiral symmetry is spontaneously broken in the vacuum by the quark-antiquark condensate, which mixes left-handed and right-handed quarks.

The broken chiral symmetry is visible at the level of the low mass part of the hadronic spectrum where there is no degeneracy between chiral partners such as the pion and the sigma mesons, the $p$ and the $a_1$ mesons, and, the nucleon and N(1535). Experimentally the $p(770)$ meson is very different from the $a_1(1260)$ meson as observed in the $\tau$-decay measured by the ALEPH collaboration.

In terms of the quark degrees of freedom, one order parameter measuring the violation of the symmetry is the quark anti-quark condensate, which in the vacuum has a value of $\langle 0 | \bar{q}q | 0 \rangle \approx -(250$ MeV)$^3 \pm 10\%$. The pion decay constant $f_\pi$ is related to the quark condensate by the Gell-Mann-Oakes-Renner (GOR) relation:

$$m_\pi^2 f_\pi^2 = -2(m_u + m_d) \langle 0 | \bar{q}q | 0 \rangle + O(m_q^4)$$  (1)

Full restoration of chiral symmetry is predicted at high temperatures and/or densities. At high enough $T$ and/or $\rho$, the quark condensate drops to zero. At normal nuclear densities and $T=0$ (i.e. the center of a heavy nucleus) the condensate is expected to drop by almost 35%. This corresponds to partial restoration of chiral symmetry. Different theories predict that the magnitude of the condensate drops quadratically with the temperature and linearly with the density of the nuclear medium.

The study of chiral symmetry restoration is one of the main goals of hadronic physics. The quark condensate is not an observable. Theoretical models are needed to relate the quark condensate to actual experimental observations. Except for the pion, no simple connection between the condensate and the properties of the particle has been established. Some models, based on QCD, try to link the condensate to average properties of particles such as their masses. Several dynamical hadronic models, with different degrees of sophistication, calculate the spectral functions of hadrons in the medium, providing much richer information than simple masses. However, the link between spectral functions and actual observable is not straightforward.

**PREDICTED MEDIUM MODIFICATIONS OF HADROMS**

There are many models predicting medium modifications of the properties of hadrons in the medium. For more details see the comprehensive reviews by Hayano and Hatsuda, Leupold, Metag and Mosel, and Norton.

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**FIGURE 1.** Predicted medium effects: (a) NJL based predictions of chiral restoration, (b) QMC mass modifications of hadrons, (c) $\rho$-meson spectral function, as a function of nuclear density.

Models using the Nambu and Jona-Lasinio (NJL) approach at finite temperatures and density predict the spectral degeneracy between the $\pi$ and the $\sigma$ meson, the $\rho$ and the $a_1$ meson in dense matter where chiral symmetry
is restored (Fig.1.a). The QCD sum rule method can relate the quark condensate to the hadronic spectral functions. QCD sum rules in the medium provide useful constraints evaluating the weighted average of the spectral functions.\(^{14}\) Hatsuda and Lee\(^ {15}\) have predicted that the mass of the vector mesons drops linearly with the density. Brown and Rho\(^ {16}\) conjectured that the masses of light mesons and the nucleon scale universally as a function of density and/or temperature.

The Quark-meson coupling model (QMC) is a phenomenological theory in which quarks and gluons are confined in a “bag” inside non-perturbative QCD vacuum.\(^ {17}\) It is interesting to note that at normal nuclear density ($\rho_0$), the $\rho$ and $\omega$ -masses have dropped by $\approx 15\%$; the nucleon-mass has dropped by $\approx 20\%$ and the D-meson mass has dropped by $\approx 3\%$ (Fig.1.b).

Hadronic models use a purely hadronic description of the mesons in the medium. The in medium self energy of the meson receives contributions from the low-energy particle-hole ($p$-$h$) excitations and the high energy nucleon–antinucleon excitations. These models provide much “richer” information about the in-medium properties of the mesons. The spectral functions are modified in non-trivial manners such as spectral shifts, spectral broadening and new spectral peaks (Fig.1.c).\(^ {18}\)

All these models make measurable predictions even at normal nuclear densities (mass shift, change in interaction, widening, extra peaks, etc.). Experimentally, one needs to measure and compare the properties of the hadrons in the vacuum and in different media (T and/or $\rho \neq 0$).

**NUCLEAR MEDIUM EFFECTS ON BOUND NUCLEONS**

The nucleus is used as a laboratory to study the changes in the properties of the nucleon. Several models predict changes in the structure functions of the nucleon, its mass and radius and the electromagnetic form factors. The EMC effect, discovered more than 25 years ago is experimentally well established\(^ {19}\) although no single model or theory describes the effect over the whole range of $x$. The effect has a weak $Q^2$ dependence and seems to be proportional to the average density with possible $\ln A$ dependence. Recent high statistics measurements at JLab on light nuclei\(^ {20}\) suggest that the local density drives the effect in nuclei such as $^4$He, $^9$Be and $^{12}$C (Fig.2.a).

Experiments looking for the Coulomb Sum Rule quenching in the medium haven’t reached a consensus. While some doesn’t observe any quenching\(^ {21}\), others seem to have established the quenching.\(^ {22}\)

The electromagnetic form factors of the nucleon are predicted to change in the medium. In the QMC model, the electromagnetic radius and the magnetic moment of the bound proton are increased.\(^ {23}\) The chiral quark soliton model\(^ {24}\) the medium modifications are significant for $G_E$ but only moderate for $G_M$.

![FIGURE 2. Medium effects on the nucleon: (a) EMC effect in C, (b) Polarization transfer ratios.](image)

The possible medium modifications of the electromagnetic form factors of the bound proton in $^4$He have been investigated in a recent high-precision experiment at JLab measuring the polarization transfer in $^4$He ($\vec{e}, e' \vec{p}$). This reaction is sensitive to possible medium modifications of the bound-nucleon form factor, while at the same time largely insensitive to other reaction mechanisms.\(^ {25}\) Currently, the polarization-transfer data can be well described by either the inclusion of medium modified form factors or strong charge-exchange final state interactions (Fig.2.b). The final analysis of these data should provide a more stringent test of these calculations.

Other studies such as short range correlations, color transparency, quark propagation in nuclear matter and general parton distributions in the medium are ongoing at all major laboratories.
MEDIUM MODIFICATION OF LIGHT MESONS

The chiral condensate in nuclear matter is predicted to drop by almost 35%. The GOR relation (equation 1) links the chiral condensate to the mass of the pion and its decay constant. Since the pion is a Goldstone boson, its mass is not expected to change dramatically with increasing nuclear density therefore a drop in the quark condensate should result in a drop in the pion decay constant. A possible way to look for this reduction is to study the in-medium pion properties through the precision spectroscopy of deeply bound pionic atoms and through the precision measurement of the low-energy pion-nucleus scattering.

Pionic Atoms

The first studies of bound pionic atoms were done by captured π− in atomic orbits and measuring transitions by X-ray spectroscopy. To “feel the medium”, the π needs to be in lowest orbits (1s, 2p). In Pb, the pion is absorbed before it can reach the lower orbits, the last observed transition is: 4f → 3d. A solution around this problem was proposed by Toki and Yamazaki and consisted in trying to “deposit” the π in the deep orbits by nuclear reactions. In 1996, the S160 experiment at GSI succeeded in observing the 2p and 1s states of pionic 207Pb using the (d,3He) reaction firmly establishing the methodology of deeply bound pionic atom spectroscopy. The S236 experiment at GSI, a follow-up experiment to S160, measured the 1s binding energies and widths in 116,120,124Sn(d,3He) reactions.

From the measured binding energies of the deeply bound states, the values of the in-medium isovector scattering length bI, the in-medium pion decay constant and the in-medium quark condensate can be derived. The current best results in the Sn isotopes suggest a drop of almost 35% of the quark condensate at normal nuclear density. This is consistent with the conclusions from low energy pion scattering at LAMPF and at PSL.

So far, this is the best experimental evidence for partial restoration of chiral symmetry in nuclear matter. These results are sensitive to the neutron skin radius and more precise experiments are planned at RIKEN. Extensive theoretical work is also underway trying to determine higher order corrections to the extraction of the in-medium quark condensate.

Double Pion Production and the Sigma Meson

The scalar-isoscalar σ-meson has been a very elusive “particle”. In the particle data book it is identified as the f0(400-1200) with a width of 400-500MeV. The σ-meson has the same quantum number as the vacuum and is interpreted as amplitude fluctuations of the quark condensate. Its properties are expected to change in the medium closely following the changes in the condensate.

The 2π production on nuclei has been studied with pion and photon beams. The CHAOS experiment at TRIUMF using pions beams on 5H, 12C, 40Ca and 208Pb, observes a substantial enhancement of correlated pions in π−π+ close to two-pions threshold for heavy nuclei. No enhancement is observed in the π+π− channel. The two-pions channels (π+π−, π0π0, π−π+, π0π+) have been studied in a photo-production experiment at the MAMI facility using the TAPS spectrometer. A significant nuclear-mass dependence of the π+π− invariant-mass distribution is found in the I=0, J=0 channel. This dependence is not observed in the other two-pions channels.

Although the observed enhancements seem consistent with a moving of the σ pole to lower masses and widths as the nuclear density increases, one has to be careful before concluding anything about chiral restoration since final state calculations without any medium effects reproduce the data reasonably well. It seems that important contributions to the “softening” of the π+π− spectra come from charge-exchange pion-nucleon scattering, which mixes the contributions from the different charge channels. Final state interactions dominate and one cannot conclusively say anything about restoration of chiral symmetry and medium changes of the σ-meson.

Light Vector Mesons

Many experiments have been studying the properties of the light vector mesons ρ, ω and φ in the medium, using simple probes such as γ, π or p on nuclei (T=0 and ρ ~ ρ0) or in relativistic heavy ion collisions (T and/or ρ > 0). Sizeable modifications of the properties of these mesons are predicted even at normal nuclear densities. The ρ meson has a very short lifetime leading to the largest probability of decaying in the medium, while the ω and φ mesons will mostly decay outside the medium in which they are produced. In order to study their in-medium properties, it is crucial to choose a proper reaction allowing the observation of slow moving ω and φ mesons. The
most interesting property of these vector mesons is that they decay into di-leptons, which have negligible final state interaction, allowing a “clean reconstruction” of the decay vertex.

However, measuring the di-lepton spectra is very challenging because of the very small branching ratio ($\sim 10^{-5}$) for this decay channel. Further complications come from the fact that there are hadronic sources that can produce leptons. One must have: i) an excellent lepton-hadron discrimination capability, ii) the ability to suppress the huge combinatorial background (severe problem in heavy ion collisions), and, iii) the ability to account for all other physics channels producing to di-leptons.

**Vector mesons in Heavy Ions Reactions (Hot and/or Dense Matter)**

The first experimental results suggesting possible medium modifications of the $\rho$-meson came from relativistic heavy-ion experiments. The CERES collaboration\(^6\) (NA45) at CERN has studied the low $e^+e^-$ invariant mass region up to $\sim 1.5$ GeV/$c^2$ in p+Be, p+Au, S+Au and reported an excess in the $e^+e^-$ mass spectrum in the $\rho$-meson region. The enhancement in the mass range between 300 and 700 MeV was originally explained as a decrease in the mass of the $\rho$-meson.\(^{37}\) However a second CERES measurement\(^{38}\) with improved mass resolution seems to favor a broadening of the $\rho$-meson rather than a simple mass shift.

The NA60 collaboration\(^{39}\) was able to extract the $\rho$-meson invariant mass spectrum and has reported a doubling of the $\rho$-meson width from their di-muon measurement in In-In collisions with no change in the $\rho$ mass.\(^{40}\) These results confirm the predictions of Rapp and Wambach.\(^{41}\)

Many other heavy ion experiments\(^{42-44}\) observe an excess of di-leptons in the region of the light vector mesons. The modification seems to rather be a substantial broadening of the $\rho$-meson rather than a simple downward mass shift. However, one should note that in $\Lambda+\Lambda$ collisions, the results are integrated over a whole range of $\rho$ and $T$. Many stages are involved in these complicated reactions, the interpretation of the results is complicated because the reaction occurs in a non-equilibrium state before proceeding to equilibrium, while most theoretical models predict the hadronic properties at equilibrium (normal nuclear density and zero temperature).

**Vector mesons in Nuclei ($T=0$ and $\rho\sim\rho_\circ$)**

The vector mesons are produced in nuclei with simple probes such as $\gamma$, $\pi$ and $p$ that leave the nucleus in almost an equilibrium state. The subsequent decay of the vector mesons in di-leptons is measured and the invariant mass spectrum is calculated.

One of the first experiments to report medium modification of the $\rho$-meson was the TAGX collaboration that reported a large decrease of the $\rho$-meson mass ($\sim 20\%$) in the reaction $^3$He$(\gamma, \pi\pi)X$, where the pion pairs result from sub-threshold $\rho$-meson production and decay.\(^{45}\) A second analysis based on the longitudinal polarization of the $\rho$ mesons reported a smaller but significant decrease in mass.\(^{46}\) However these results are questionable given the small density of the nucleus and the final-state interactions on the pion pairs.

The experiment E325 at the KEK 12 GeV Proton Synchrotron was the first to measure di-leptons in search for the modification of the vector meson mass in a nucleus. They measured the invariant mass spectra of $e^+e^-$ pairs produced in 12 GeV proton-induced nuclear reactions. Figure 3.a shows the background subtracted di-lepton invariant mass spectra measured on Cu with the best fit results.\(^{47,48}\) These fits indicate a downward mass shift of 9.2 ± 0.2 % for the $\rho$ meson and no change in the widths of the $\rho$ and $\omega$ mesons. The analysis of the “slow moving” $\phi$-meson shows a downward mass shift of $3.4 \pm 0.6\%$ of its mass and an increase of a factor 3-4 of its width.

The CBELSA/TAPS collaboration at the electron stretcher accelerator (ELSA) in Bonn used the $\gamma\Lambda \rightarrow \pi^0\gamma X$ reaction to study the $\omega$ meson in-medium behavior in LH$_2$ and Nb. The branching ratio for $\omega \rightarrow \pi^0\gamma$ decay is the order of 9%. This channel provides a clean and exclusive mode to study the $\omega$ in-medium properties. The $\rho$ is highly suppressed since the $\rho \rightarrow \pi^\circ\gamma$ branching ratio is $< 10^{-3}$. However, a serious disadvantage is the possible strong final-stage interactions of the $\pi^0$ meson within the nucleus. In order to maximize the in nucleus decay probability, slow-moving $\omega$-mesons with $|p_{\omega}| < 0.5$ GeV/$c$ were selected. In a first analysis, a shoulder on the low-mass side of the $\omega$ peak was found in the Nb target and was interpreted as medium modified $\omega$-mesons with a downward mass shift of 14%.\(^{49}\) In a reanalysis of the data, the shoulder has disappeared (Fig. 3.b) and the results are compatible with no mass shift.\(^{50}\) Therefore, until final results are published, the $\omega$ in medium studies in this channel should be considered as inconclusive.
The cross section was deduced to be \( \sigma \) using the transparency ratio \( T \) defined (for a vector meson \( V \)) as:

\[
T_A = \frac{\sigma_{A \rightarrow VX}}{\sigma_{\gamma N \rightarrow VX}}
\]  

(2)

\( \sigma_{\gamma A \rightarrow VX} \) is the inclusive nuclear vector-meson (\( V \)) photo-production cross section and \( \sigma_{\gamma N \rightarrow VX} \) is cross section on a free nucleon. The transparency ratio \( T \) is a measure of the loss of vector-meson flux via inelastic processes in the nucleus, and is related to the absorptive part of the meson-nucleus potential. Extracting the in-medium meson width from the A dependence of the ratio \( T \) requires comparison with theoretical calculations.\(^{34,55}\)

For the \( \omega \)-meson measured in the JLab \( g7 \) experiment, the transparency ratios are derived for the \( ^2 \)H, C, Fe/Ti, and Pb and compared to the TAPS data\(^{56}\) and theoretical calculations. The transparency ratios decrease rapidly as a function of A, indicating a substantial increase in the in-medium width of the \( \omega \). The JLab ratios drop faster that the CBELSA-TAPS ratios indicating an even larger in-medium width (\( \Gamma_\omega \geq 200 \) MeV). The TAPS collaboration has published a value of \( \Gamma_\omega \sim 130-150 \) MeV. The experimental ratios are compared to theoretical predictions from the Giessen group\(^{57}\) and Valencia group.\(^{58}\) The very large \( \omega \)-meson absorption observed in the \( e^+e^- \) channel cannot be explained with the current theoretical calculations.

The photo-production of \( \phi \) mesons from Li, C, Al and Cu targets has been measured at \( E_\gamma = 1.5 - 2.4 \) GeV at SPring-8 (LEPS), in the \( \gamma A \rightarrow K^+K^-X \) channel.\(^{59}\) Using a Glauber-type model calculation, the in-medium \( \phi \)-nucleon cross section was deduced to be \( \sigma_{\eta N} = 37[17, -11] \) mb, which is much larger than the free-space value used as an input in most model calculations. The SPring8 results are compatible within statistical uncertainties with the JLab results and seem to indicate an in-medium width for the \( \phi \) as large as \( \Gamma_\phi \sim 70 \) MeV.
SUMMARY AND CONCLUSIONS

The study of the modifications of the properties of hadrons in the medium is one of the main topics of research in hadronic physics. The many ongoing theoretical and experimental studies attest to the vibrancy of this field. QCD is the fundamental theory of the strong interactions and a lot of progress has been achieved in trying to describe nuclear and hadronic physics in terms of the fundamental degrees of freedom (quarks and gluons).

Since the EMC effect observed a modified structure function for the bound nucleon, many other experiments have been studying the effect of the medium on the nucleon. Polarization observables look promising and might help distinguish between final state interactions and genuine medium modifications.

The quark condensate is predicted to change in hot and/or dense medium as a function of temperature \( T \) and density \( \rho \). In ordinary nuclear matter, the value of the quark condensate is predicted to drop by 35% indicating a partial restoration of chiral symmetry. The strongest evidence comes from deeply bound pionic states where the results suggest an in-medium drop of the \( \pi N \) isovector scattering length \( b_1 \) which indicates a 33% drop of the condensate in normal nuclear matter. The study of the in-medium properties of light vector mesons (\( \rho, \omega \) and \( \phi \)) is interesting because of their leptonic decay channel. Experiments looking at the di-lepton decay of the vector mesons range from heavy-ion collisions to elementary reactions with \( \gamma, \pi \) and \( \rho \).

In all heavy-ion reactions, an excess of di-leptons is observed in the region of the light vector mesons. This excess can be explained by a substantial widening of the \( \rho \) with no mass shift. Several elementary reactions experiments have reported medium modifications for the \( \rho \), the \( \omega \) and the \( \phi \). A broadening in the nuclear medium has been reported by almost all experiments. For the \( \rho \) meson quantitative agreement between theory and experiment has been achieved while for the \( \omega \) and \( \phi \) meson the broadening deduced from transparency-ratio measurements is a factor 2-3 larger than predicted theoretically. The majority of experiments does not find evidence for mass shifts in the medium. For the \( \rho \) meson only one experiment (KEK) reports a drop of 9% in mass. Looking for in-medium mass shifts turns out to be more complicated than initially thought because of the observed large in-medium broadening. The \( \omega \) and \( \phi \) meson are narrow in vacuum but are found to widen by a factor of the order of 15 in nuclear matter. This drastically reduces the branching ratio for in-medium decays into the channels of interest, making these experiments less sensitive to a direct observation of medium modifications. Next generation experiments with much higher statistics and improved acceptance for low momenta mesons are needed to obtain reliable results. Several experiments are planned at JPARC, JLab, RHIC, FAIR and CERN. During the next decade, substantial theoretical and experimental efforts will continue to be being carried out in this very active field.

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