There is currently enormous interest in the investigation of how hadron properties may be altered by immersion in matter. There is strong evidence of a reduction in the mass of the rho meson from relativistic heavy ion collisions as well as a hint from a recent experiment on photoproduction in light nuclei. We briefly review the main theoretical ideas which lead one to expect the mass of a hadron to change in matter, including the various QCD-based methods, notably the QCD sum rules, as well as mean-field, quark based models like QMC and conventional nuclear approaches such as QHD.

1. INTRODUCTION

Over the past decade there has been a great deal of theoretical work directed at understanding how hadronic properties change in nuclear matter. Recently this activity has been stimulated by the evidence from relativistic heavy ion collisions that the mass of the $\rho$ meson in matter may be several hundred MeV lower at 2-3 times nuclear matter density. We begin with a brief reminder of this experimental evidence. Then we turn to recent theoretical developments, including QHD, the quark meson coupling model (QMC) and QCD sum rules, including the effect of absorptive channels. In conclusion we mention recent experimental work which aims to detect the shift of the $\rho$ mass in light nuclei using sub-threshold photo-production.

2. RELATIVISTIC HEAVY ION COLLISIONS

There is a variety of experiments underway at CERN (CERES and HELIOS-3) and GSI (HADES) and planned at RHIC which aim to produce high density hadronic matter through the collision of relativistic heavy ions. In the collisions of $S$ on $Au$ at SPS/CERN at 200 GeV there is a large excess of $e^+e^-$ pairs in the invariant mass region around 400 MeV. Numerical simulations of the collision dynamics suggest that the region of hot dense matter formed in such a collision (the “fire cylinder”) should occupy a volume about 7fm in diameter and 4fm long. At formation it should have a peak density around $2 - 3\rho_0$ (with $\rho_0$ the saturation density of symmetric nuclear matter) and contain roughly
100 baryons, 100 pions and perhaps 50 $\rho$ and $\omega$ mesons [2]. The most straightforward explanation of the excess lepton pairs is that the mass of the $\rho$ meson in matter at such densities is lowered to between 400 and 600 MeV [3].

Of course, the dynamics of matter under such extreme conditions is very much an unknown area and there are alternative mechanisms which have been suggested to explain the excess. For example, in relation to the CERES data, Chanfray et al. [4] have emphasised the importance of channels such as $\pi N$ and $\pi \Delta$ which may produce an enhancement in the number of pions in the system. These can then annihilate into lepton pairs. It may be some time before there is a consensus on the mechanism involved and new data, particularly involving systems such as $Pb$ on $Pb$, which should produce an even larger fire cylinder, will play a vital role. Nevertheless, the theoretical efforts to understand the behaviour of hadrons in dense matter have received a tremendous stimulus because of the enhancement in precisely the region one expects if the $\rho$ mass decreases in the way many theoretical approaches have suggested.

3. THEORETICAL DEVELOPMENTS

A great deal of the recent theoretical on the possible decrease of hadron masses in nuclear matter has also been stimulated by the suggestion of Brown-Rho scaling [3]. Starting with a chiral soliton model of nuclear matter these authors suggested the following behaviour for the variation of key parameters with density:

$$\frac{m^*_V}{m_V} \approx \frac{m^*_N}{m_N} \approx \frac{m^*_\sigma}{m_\sigma} \approx \left( \frac{\langle r^2 \rangle_N}{\langle r^2 \rangle_N^*} \right)^{1/2} \approx \frac{f^*_\pi}{f_\pi}. \quad (1)$$

As $f^*_\pi$ is expected to vanish as chiral symmetry is restored at high density all of the masses in Eq.(1) (i.e., the vector meson masses, $m_V$, the nucleon mass $m_N$ and the $\sigma$ meson mass $m_\sigma$) are expected to decrease as the density increases. Taking as a guide the reduction of the ratio $m^*_N/m_N$ calculated in QHD, that is around 0.6 at $\rho_0$, one expects the $\rho$ mass to be as low as 500 MeV, even at normal nuclear matter density.

On the other hand, there are very strict limits on the possible variation of the size of the nucleon in nuclear matter [8]. The mean square radius of the nucleon cannot vary by more than perhaps 5% and Eq.(1) is in clear contradiction with such a limit. It remains to be seen whether it is possible to generalise the Brown-Rho analysis to relax the condition on the nucleon radius while retaining the results for the masses. In any case, the main point of that work is the stimulus it has provided to the field.

3.1. Quantum Hadrodynamics

Quantum hadrodynamics (QHD) developed out of the wish to have a renormalizable, covariant theoretical framework for nuclear physics [7]. In its simplest form, QHD involves a system of point-like, Dirac nucleons coupled to elementary scalar ($\sigma$) and vector ($\omega$) isoscalar mesons. In Hartree approximation the self consistent solution for nuclear matter leads to a nucleon effective mass at saturation density of about 60% of the free mass. Going beyond Hartree approximation tends to yield a value more in the range 70–80%.

The first study of the mass of a vector meson (in this case the $\omega$) within QHD was by Saito, Maruyama and Soutome [8]. For a recent review we refer to the work of Cohen et
All of the studies within QHD tend to lead to a lowering of the mass of the \( \omega \), mainly because of the coupling to \( NN \) states. (Without that the effect of particle-hole excitations would be to raise the mass.) This has led Saito and Thomas to question the sign of the effect in a QHD-type model in the case where the coupling to \( NN \) states is suppressed by the finite size of the nucleon \[10\].

One other aspect of the QHD treatment that has so far not been sufficiently appreciated is the finding of Jean, Piekarewicz and Williams \[11\] that the shift of the \( \omega \) mass is not only momentum dependent but that the shift is different for transversely polarized and longitudinally polarized mesons (i.e., \( m^T \neq m^L \)). (This was also emphasised more recently by Eletsky and Ioffe \[12\].) The latter could be particularly important for the analysis of real experimental data. For a vector meson at rest these authors found a very similar mass shift to that in earlier work, with the effective mass of the meson about 80\% of its free value at nuclear matter density.

### 3.2. The Quark Meson Coupling Model

A truly consistent theory capable of describing the transition from meson and baryon degrees of freedom to quarks and gluons might be expected to incorporate the internal quark and gluon degrees of freedom of the particles themselves. The quark meson coupling (QMC) model was originally suggested by Guichon \[13\] in order to investigate precisely these effects. It has since been developed extensively \[14–17\] for nuclear matter and extended to provide a very realistic description of finite nuclei \[18–20\].

Within the QMC model the properties of nuclear matter are determined by the self-consistent coupling of scalar (\( \sigma \)) and vector (\( \omega \)) fields to the quarks within the nucleons, rather than to the nucleons themselves. As a result of the scalar coupling the internal structure of the nucleon is modified with respect to the free case. In particular, the small mass of the quark means that the lower component of its wave function responds rapidly to the \( \sigma \) field, with a consequent decrease in the scalar density. As the scalar density is itself the source of the \( \sigma \) field this provides a mechanism for the saturation of nuclear matter where the quark structure plays a vital role.

In a simple version of the model, where nuclear matter was considered as a collection of static, non-overlapping bags it was shown that a satisfactory description of the bulk properties of nuclear matter can be obtained \[10,13\]. Of particular interest is the fact that the extra degrees of freedom, corresponding to the internal structure of the nucleon, result in a lower value of the incompressibility of nuclear matter than obtained in approaches based on point-like nucleons – such as QHD \[7\] – at least at the same level of sophistication (Hartree approximation). In fact, the prediction is in agreement with the experimental value once the binding energy and saturation density are fixed. Improvements to the model, including the addition of Fermi motion, have not altered the dominant saturation mechanism. Furthermore, it is possible to give a clear understanding of the relationship between this model and QHD \[21\]. Surprisingly the model seems to provide a semi-quantitative explanation of the Okamoto-Nolen-Schiffer anomaly when quark mass differences are included \[22\]. Finally the model has been applied to the case where quark degrees of freedom are undisputedly involved – namely the nuclear EMC effect \[23\].

Our main interest is in the predictions of the model for the variation of hadron masses in dense matter. As the \( \omega \) and \( \rho \) are simple \( q\bar{q} \) states in QCD, the QMC model has been
generalised to allow for the self-consistent determination of the vector meson masses as well as the nucleon mass \([24]\). The variation of the resulting nucleon and \(\omega\) masses are shown in Figs. 1 and 2 as a function of the density of symmetric nuclear matter \([24]\). At low density the behaviour of these mass variations is well approximated by a term linear in the density:

\[
\frac{M^*_N}{M_N} \simeq 1 - 0.21 \left( \frac{\rho_B}{\rho_0} \right),
\]

(2)

and

\[
\frac{m^*_v}{m_v} \simeq 1 - 0.17 \left( \frac{\rho_B}{\rho_0} \right).
\]

(3)

Using the QMC model it was also possible to study the variation of the masses of the \(\Lambda, \Sigma\) and \(\Xi\) as well. From these calculations we were led to a new, simple scaling relation between the hadron masses \([24]\):

\[
\left( \frac{\delta m^*_v}{\delta M^*_N} \right) \simeq \left( \frac{\delta M^*_\Lambda}{\delta M^*_N} \right) \simeq 2 \quad \text{and} \quad \left( \frac{\delta M^*_\Sigma}{\delta M^*_N} \right) \simeq \frac{1}{3},
\]

(4)

where \(\delta M^*_j \equiv M_j - M_j^*\). The factors, \(\frac{2}{3}\) and \(\frac{1}{3}\), in Eq.(4) come from the ratio of the number of non-strange quarks in \(j\) to that in the nucleon. This means that the hadron mass is primarily determined by the number of non-strange quarks. These experience the
Figure 2. Effective ($\rho$- or) $\omega$-meson mass in symmetric nuclear matter – from Ref.[24].

common scalar field generated by surrounding nucleons in medium, and the strength of the scalar field.

In view of the interest in the CERES results noted earlier, it is interesting to estimate the shift in the mass of the $\rho$ meson predicted by the QMC model at the appropriate densities. At $\rho_0$ we find $m_{\rho} - m^*_\rho \approx 140$MeV, while at $2\rho_0$ we find $m^*_\rho \approx 580$MeV. The latter is certainly in the right range needed to understand the excess leptons observed in the experiment.

3.2.1. Constraints on the QMC model

We have already noted the strong constraints on the possible variation of the internal structure of the nucleon from $y$-scaling [6]. It has only recently proven possible to accurately calculate the variation of the nucleon electromagnetic form factors within the QMC model and check that they are consistent with existing constraints [25]. Figure 3 shows the results and we see that the variation of the magnetic form factors (which tend to be the most important) is particularly small.

3.2.2. Possible connection to QCD

The saturation mechanism within the QMC model is rather more general than the bag upon which it was based. Indeed, the details of the internal structure of the nucleon do not appear in the final equations, all one needs is the density dependence of the coupling constant of the scalar meson to the “nucleon”. It would be extremely interesting to see whether this could be calculated directly from QCD -either on the lattice or through the Dyson-Schwinger approach. If it were possible to input this variation from such a calculation one would, in a very real sense, have a means to calculate nuclear properties from QCD itself.
Figure 3. The nucleon electromagnetic form factors in the nuclear medium (calculated within the QMC model) relative to those in free space case – from Ref.[25].

4. QCD SUM RULES

The QCD sum rule technique is used to relate two evaluations of a current-current correlator. On one side, the correlator is evaluated using the operator product approach to QCD to yield an expression which is valid at large momentum transfer. For example, if we write the $\rho - \rho$ correlator, $\Pi^{\mu\nu}$, as $(g^{\mu\nu} - q^{\mu}q^{\nu}/q^2)\Pi$, then (using $-q^2 = Q^2 > 0$) one finds:

$$\frac{12\pi}{Q^2} \Pi(Q^2) = \frac{d}{\pi} \left[ -c_0\ln\frac{Q^2}{\mu^2} + \frac{c_1}{Q^2} + \frac{c_2}{Q^4} + \ldots \right].$$

In Eq.(5) the term in $1/Q^2$ involves the quark masses, the $1/Q^4$ term the quark and gluon condensates, the $1/Q^6$ term the 4-quark condensate, and so on. On the other side, one writes a dispersion relation in which the $\rho$ meson is often approximated by a simple pole and the continuum by a simple $\theta$-function. The Borel transform is often employed to make the region over which the two sides can be equated large enough to check whether they match well.
In free space the QCD sum rule technique appears to work well and the shape of the imaginary part of $\Pi$ ($Im\Pi$) is relatively well described by vector meson dominance. In matter one needs to allow for the variation of the various condensates and to modify the dispersion relation to describe the hadron in medium \[26\]. Hatsuda \textit{et al.} concluded that the mass of the $\rho$ should behave in a very similar manner to that found in QMC (c.f., Eq.\,(3) above) \[27\]:

$$\frac{m^*_V}{m_V} \approx 1 - 0.18 \frac{\rho}{\rho_0} \quad (6)$$

Jin and Leinweber found an almost identical result \[29\], but with somewhat larger errors, corresponding to a realistic estimate of the current state of knowledge of all the relevant parameters, $m^*_V/m_V = 0.78 \pm 0.08$.

An important new observation concerning this problem was made recently by Klingl \textit{et al.} \[30\] – see also Asakawa and Ko \[31\]. These authors estimated the effect of the coupling of the $\rho(\omega)N$ system to $\pi N, \pi\pi N, \Sigma K$ etc. Using a phenomenological Lagrangian based on chiral $SU(3)$ symmetry they showed that the effect of absorption could be very strong. In the case of the $\rho$, the shape of the $Im\Pi(s)$ usually used was shown to be quite wrong. While the spectral function was much broader and appeared to peak at a much lower invariant mass it was clear from the real part that the mass of the $\rho$ had not shifted significantly.

The analysis of Klingl \textit{et al.} omitted the mean-field scalar attraction that usually leads to a lowering of the mass of a hadron in matter. It also omitted the effect of s-channel, baryon resonances which could be important in some circumstances. Nevertheless, this work has served to remind people working in this field that the very notion of a hadron “mass” in medium is a model dependent concept. One is really looking at the response of the medium in a specific channel.

5. AN ALTERNATIVE EXPERIMENT

While most attention is focussed on the experiments involving relativistic heavy ions and matter under extreme conditions, it would also be very important to measure a shift in normal nuclei. An attempt to do just this is currently underway at TJNAF (following the initial proposal by Bertin and Guichon \[32,33\]) and at INS \[34\]. The INS experiment aimed to measure sub-threshold $\rho^0$ photoproduction on light nuclei such as $^{3,4}\text{He}$ and $^{12}\text{C}$ using the TAGX spectrometer at the 1.3GeV Tokyo Electron Synchrotron. Light nuclei offer the advantage of less final state interactions for the outgoing $\pi^+\pi^-$ pairs. Initial results presented at this meeting suggest evidence that the mass of the $\rho$ may be somewhat lower than the free case, even for $^{3}\text{He}$ \[35\].

In order to estimate the size of the effects expected in the TAGX experiment, Saito \textit{et al.} \[36\] have used the latest version of the QMC model, in which the meson masses are self-consistently obtained in the mean scalar field of the nucleus \[24\]. As the mean field description is not good for a nucleus as light as $^{3}\text{He}$ the effective mass as a function of position in the nucleus was estimated in local density approximation using a phenomenological density distribution. Both the form used and the effective mass of the $\rho$ are shown in Fig. 4. On average the mass of the $\rho$ is shifted down by about 40MeV in this case. It
Figure 4. Effective $\rho$-meson mass and the density distribution in $^3$He. The solid, dashed and dotted curves correspond to the same parameter sets used in Figs. 1 and 2 (above) – from Ref.[36].

will be very interesting to see the final results of this experiment for both the coherent and incoherent $\rho$ production. A comparison with data on a slightly heavier nucleus such as $^{12}$C would also be very useful.

In the light of the results of Klingl et al. [30], discussed earlier, it will also be important to improve this first estimate by estimating the effect of coupled, absorptive channels. This is also clearly relevant to the TJNAF experiment, where the comparison of the rather different behaviour expected of the $\rho$ and $\omega$ was anticipated to provide an important signal [32].

6. CONCLUSION

The study of the variation of hadron properties in matter is fundamental to our developing understanding of the strong interaction. As temperature and density vary we expect to see a shift in the relative importance of quark and hadron degrees of freedom. There are already tantalising hints from CERES that the mass of the $\rho$ meson may decrease rather dramatically with increasing density. Even in a nucleus as light as $^3He$, the TAGX experiment suggests that it may also decrease. We may expect a great deal more experimental information in the coming years.

The theoretical consensus seems to be that without channel coupling (absorptive) effects the mass of a vector meson should decrease by about 150–200 MeV at $\rho_0$. The situation with respect to the mass of virtual $\rho$ and $\omega$ mesons is much less clear. One might expect
the effect of channel coupling to be attractive in this case. Nor is there a consensus on
the behaviour of the $\sigma N$ coupling constant in matter. It is a very fundamental issue for
QCD whether the nucleon acts as a dia-scalar.

On the basis of approaches such as the QMC model, there can be little doubt that the
structure of the bound “nucleon” is significantly different from that of the free nucleon.
What occupies the shell-model orbits in finite nuclei are quasi-particles with nucleon
quantum numbers $[18]$. It will be important to explore further the corresponding changes
in properties (other than mass) and to check calculations of such effects against the
best available experimental information.

This is a very exciting time to be working in this field and we eagerly await the next
theoretical and experimental developments.

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