Variation of hadron masses in finite nuclei

Koichi SAITO
Physics Division, Tohoku College of Pharmacy
Sendai 981, Japan
E-mail: ksaito@nucl.phys.tohoku.ac.jp

Kazuo TSUSHIMA and Anthony W. THOMAS
Department of Physics and Mathematical Physics, University of Adelaide
Adelaide, SA 5005, Australia

Using a self-consistent, Hartree description for both infinite nuclear matter and finite nuclei based on a relativistic quark model (the quark-meson coupling model), we investigate the variation of the masses of the non-strange vector mesons, the hyperons and the nucleon in infinite nuclear matter and in finite nuclei.

1 Introduction

One of the most interesting future directions in nuclear physics may be to study how nuclear matter properties change as the environment changes. Forthcoming ultra-relativistic heavy-ion experiments are expected to give significant information on the strong interaction (i.e., QCD) in matter, through the detection of changes in hadronic properties.

In particular, the variations in hadron masses in finite nuclei have attracted wide interest because such changes could be a signal of the formation of hot hadronic and/or quark-gluon matter in energetic nucleus-nucleus collisions. Several authors have studied the vector-meson ($\omega, \rho, \phi$) masses using the vector dominance model, QCD sum rules and the Walecka model (QHD), and have reported that these masses decrease in the nuclear medium.

Using a self-consistent, Hartree description for both nuclear matter and finite nuclei in the quark-meson coupling (QMC) model, we report on the variation of the masses of the non-strange vector mesons, the hyperons and the nucleon in finite nuclei.

2 The QMC model

The QMC model may be viewed as an extension of QHD in which the nucleons still interact through the exchange of $\sigma$ and $\omega$ mesons. However, the mesons couple not to point-like nucleons but to confined u and d quarks. In studies of infinite nuclear matter, it was found that the extra degrees of freedom provided by the internal structure of the nucleon mean that one gets quite an acceptable value for the incompressibility once the coupling constants are chosen to reproduce the correct saturation.
energy and density for symmetric nuclear matter. This is a significant improvement on QHD at the same level of sophistication. There have been several interesting applications to the properties of finite nuclei using the local-density approximation.

In Ref. we extended the QMC model to finite nuclei in the Born-Oppenheimer approximation. The QMC model not only reproduces the saturation properties of nuclear matter but also describes fairly well the observed charge density distributions and neutron density distributions of static, closed-shell nuclei from $^{16}$O to $^{208}$Pb (see also Ref.6). The basic result in the QMC model is that, in the scalar ($\sigma$) and vector ($\omega$) meson fields, the nucleon behaves essentially as a point-like particle with an effective mass $M_N^\ast$ (which depends on the position only through the $\sigma$ field) moving in a vector potential generated by the $\omega$ meson.

To calculate the variation of hadron masses in finite nuclei, it is necessary to include the effect of not only the changes in nucleon structure but also those of the mesons in the model. Because of the vector character, the vector interactions have no effect on the hadron structure except for an overall phase in the wave function, which gives a shift in the hadron energy. Therefore, our effective Lagrangian density in mean field approximation takes the form:

$$\mathcal{L}_{QMC} = \overline{\psi}(i\gamma \cdot \partial - M_N + g_\sigma(\sigma(\vec{r}))\sigma(\vec{r}) - g_\omega(\omega(\vec{r}))\gamma_0 \psi$$

$$- \frac{1}{2}g_\rho(\rho(\vec{r}))\gamma_0 - e(1 + \tau_3^N)A(\vec{r})\gamma_0 \psi$$

$$- \frac{1}{2}[(\nabla\sigma(\vec{r}))^2 + m_\sigma^\ast(\sigma)^2\sigma(\vec{r})^2] + \frac{1}{2}[(\nabla\omega(\vec{r}))^2 + m_\omega^\ast(\sigma)^2\omega(\vec{r})^2]$$

$$+ \frac{1}{2}[(\nabla b(\vec{r}))^2 + m_\rho^\ast(\sigma)^2b(\vec{r})^2] + \frac{1}{2}(\nabla A(\vec{r}))^2,$$

where we notice that the vector meson masses depend on only the $\sigma$ field at the point $\vec{r}$ in the nucleus.

3  A new scaling phenomenon in hadron masses

In the QMC model the changes in the hadron masses can be described in terms of the common scalar ($\sigma$) field in nuclei (see also Ref.3). Supposing that a strange quark does not couple to the scalar field directly, the decrease of the hadron mass is well approximated by

$$\delta M_j^\ast \equiv M_j - M_j^\ast \simeq \frac{n_0}{3}(g_\sigma(\sigma(0))) \left[1 - \frac{a_j}{2}(g_\sigma(\sigma))\right],$$

where $M_j(M_j^\ast)$ is the hadron mass ($j = N, \omega, \rho, \Lambda$, etc) in free space (matter), $n_0$ is the number of non-strange quarks in the hadron and $a_j$ is a constant depending on the hadron structure – it ranges around $8.5 \sim 9.5 \times 10^{-4}$ (MeV$^{-1}$) for $N, \omega, \rho, \Lambda$ and...
Ξ. At low density we find that the mass reduction is
\[
\frac{M^*_j}{M_j} \simeq 1 - \frac{n_0}{3} \left[ \frac{g_\sigma \sigma(r)}{M_j} \right], \quad \text{and} \quad g_\sigma \sigma \simeq 200(\text{MeV}) \left( \frac{\rho_B}{\rho_0} \right),
\]
and we then get
\[
\frac{M^*_N}{M_N} \simeq 1 - 0.2 \left( \frac{\rho_B}{\rho_0} \right), \quad \frac{m^*_\omega}{m_\omega} \simeq 1 - 0.16 \left( \frac{\rho_B}{\rho_0} \right), \quad \frac{M^*_\Lambda}{M_\Sigma} \simeq 1 - 0.11 \left( \frac{\rho_B}{\rho_0} \right), \quad \frac{M^*_\Xi}{M_\Xi} \simeq 1 - 0.05 \left( \frac{\rho_B}{\rho_0} \right).
\]
Since the dependence of the constant \( a_j \) on the hadrons is weak (in Eq.(2)), our results lead to a new scaling relation describing the variation of hadron masses with density:
\[
\frac{\delta M^*_\omega}{\delta M^*_N} \simeq \frac{\delta M^*_\Lambda}{\delta M^*_N} \approx \frac{2}{3}, \quad \frac{\delta M^*_\Xi}{\delta M^*_N} \approx \frac{1}{3}, \quad \text{etc.}
\]
This scaling is relevant over the range of \( \rho_B \) up to \( \sim 3\rho_0 \).

4 Hadron masses in finite nuclei

![Figure 1](image.png)

Figure 1. The variation of nucleon, \( \omega \) and \( \sigma \) meson masses in \(^{208}\text{Pb}\). The nuclear baryon density, \( \rho_B \), is also shown. The right (left) scale is for the effective mass (the baryon density).

Using the effective Lagrangian density, Eq.(1), we have performed some self-consistent calculations of the variation of hadron masses in finite nuclei – for example,
the initial result for $^{208}$Pb is shown in Fig.1 (we will present detailed numerical studies elsewhere).

In this model it is, however, hard to deal with the change of the $\sigma$-meson mass in medium because it couples strongly to the pseudoscalar ($\pi$) channel, which requires a direct treatment of chiral symmetry in medium\cite{8}. Here we suppose that $m^*_\sigma$ in Eq.(1) is also given by the same form as those of the vector mesons – see Eq.(2).

As shown in the figure the $\omega$-meson mass is reduced about 15% while the nucleon and the $\sigma$-meson masses decrease about 20% in the interior of Pb, which are also expected in other various models\cite{5}.

5 Summary

We have studied the spectral change of the hadrons in both nuclear matter and finite nuclei using the extended QMC model. As several authors have suggested\cite{1,2}, the hadron mass is reduced due to the change of the scalar mean-field in medium. In the present model the hadron mass can be related to the number of non-strange quarks and the strength of the scalar mean-field. The hadron masses are simply connected to one another, and the relationship among them is given by Eq.(5), which is effective over a wide range of the nuclear density. Furthermore, we have shown the variation of the hadron masses in lead. It will be quite important to perform such calculations for finite nuclei in order to interpret the results observed in forthcoming ultra-relativistic heavy-ion experiments.

This work was supported by the Australian Research Council.

1. HELIOS-3 collaboration, *Nucl. Phys.* A590 (1995) 93c.
   CERES collaboration, *ibid.* A590 (1995) 103c.
   G.Q. Li, C.M. Ko and G.E. Brown, nucl-th/9608040 (1996).
2. For summary, T. Hatsuda, nucl-th/9608037 (1996).
3. P.A.M. Guichon, *Phys. Lett.* B200 (1988) 235.
   K. Saito and A.W. Thomas, *Phys. Lett.* B327 (1994) 9.
4. K. Saito and A.W. Thomas, *Phys. Lett.* B335 (1994) 17.
   K. Saito and A.W. Thomas, *Nucl. Phys.* A574 (1994) 659.
   K. Saito and A.W. Thomas, *Phys. Lett.* B363 (1995) 157.
5. P.A.M. Guichon et al., *Nucl. Phys.* A601 (1996) 349.
   K. Saito et al., Univ. of Adelaide preprint ADP-96-17/T220 (nucl-th/9606024, 1996), to appear in *Nucl. Phys.* A.
6. K. Tsushima et al., these Proceedings.
7. K. Saito and A.W. Thomas, *Phys. Rev.* C51 (1995) 2757.
8. T. Hatsuda and T. Kunihiro, *Phys. Rep.* 247 (1994) 221.