Rho-meson mass in light nuclei

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Abstract

The quark-meson coupling (QMC) model is applied to a study of the mass of the \( \rho \)-meson in helium and carbon nuclei. The average mass of a \( \rho \)-meson formed in \( ^3\text{He} \) and \( ^{12}\text{C} \) is expected to be around 730, 690 and 720 MeV, respectively.

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As the nuclear environment changes, hadron properties are nowadays expected to be modified [1, 2, 3, 4, 5, 6]. In particular, the variation of the light vector-meson mass is receiving a lot of attention, both theoretically and experimentally. Recent experiments from the HELIOS-3, CERES and NA50 collaborations at SPS/CERN energies have shown that there exists a large excess of the lepton pairs in central S + Au, S + W, Pb + Au and Pb + Pb collisions [7]. An anomalous $J/\psi$ suppression in Pb + Pb collisions has also been reported by the NA50 collaboration [8]. Those experimental results may give a hint of some change of hadron properties in nuclei (for a recent review, see Ref. [9]). We have previously studied the variation of hadron masses in medium mass and heavy nuclei using the quark-meson coupling (QMC) model [4, 10].

On the other hand, even in light nuclei like helium and carbon, an attempt to measure the $\rho^0$-meson mass in the nucleus is underway at INS, using tagged photon beams and the large-acceptance TAGX spectrometer at the 1.3 GeV Tokyo Electron Synchrotron [11]. They have measured $\rho^0$ decay into two charged pions with a branching fraction of approximately 100% in low-atomic-number nuclei, in which pions suffer less from final state interactions. The actual experiments involved measurements of the $\pi^+\pi^-$ photoproduction on $^3$He, $^4$He and $^{12}$C nuclei in the energy region close to the $\rho^0$ production threshold. In view of this experimental work it is clearly very interesting to report on the variation of the $\rho$-meson mass in these light nuclei.

To calculate the hadron mass in a finite nucleus, we use the second version of the quark-meson coupling (QMC-II) model, which we have recently developed to treat the variation of hadron properties in nuclei (for details, see Ref. [10]). This model was also used to calculate detailed properties of spherical, closed shell nuclei from $^{16}$O to $^{208}$Pb, where it was shown that the model can reproduce fairly well the observed charge density distributions, neutron density distributions, etc. [12]. In this approach, which began with work by Guichon [13] in 1988, quarks in non-overlapping nucleon bags interact self-consistently with scalar ($\sigma$) and vector ($\omega$ and $\rho$) mesons (the latter also being described by meson bags), in the mean-field approximation (MFA). Closely related investigations
have been made in Refs. [14, 15, 16].

In the actual calculation, we use the MIT bag model in static, spherical cavity approximation. The bag constant $B$ and the parameter $z_N$, in the familiar form of the MIT bag model Lagrangian [17], are fixed to reproduce the free nucleon mass ($M_N = 939$ MeV) and its free bag radius ($R_N = 0.8$ fm). Furthermore, to fit the free vector-meson masses, $m_\omega = 783$ MeV and $m_\rho = 770$ MeV, we introduce new $z$-parameters for them, $z_\omega$ and $z_\rho$. Taking the quark mass in the bag to be $m_q = 5$ MeV, we find $B^{1/4} = 170.0$ MeV, $z_N = 3.295$, $z_\omega = 1.907$ and $z_\rho = 1.857$ [10].

The model has several coupling constants to be determined: the $\sigma$-nucleon coupling constant (in free space), $g_\sigma$, and the $\omega$-nucleon coupling constant, $g_\omega$, are fixed to fit the binding energy ($-15.7$ MeV) at the correct saturation density ($\rho_0 = 0.15$ fm$^{-3}$) for symmetric nuclear matter. Furthermore, the $\rho$-nucleon coupling constant, $g_\rho$, is used to reproduce the bulk symmetry energy, 35 MeV. Those values are listed in Tables 1 and 3 of Ref. [10].

Within QMC-II, the non-strange vector mesons are described by the bag model and their masses in the nuclear medium are given as a function of the mean-field value of the $\sigma$ meson at that density [10]. However, the $\sigma$ meson itself is not so readily represented by a simple quark model (like a bag), because it couples strongly to the pseudoscalar (2$\pi$) channel and a direct treatment of chiral symmetry in medium is important [3].

On the other hand, many approaches, including the Nambu–Jona-Lasinio model [3, 18], the Walecka model [1, 19] and Brown-Rho scaling [2] suggest that the $\sigma$-meson mass in medium, $m_\sigma^*$, should be less than the free one, $m_\sigma$. We have parametrized it using a quadratic function of the scalar field:

$$\left(\frac{m_\sigma^*}{m_\sigma}\right) = 1 - a_\sigma (g_\sigma \sigma) + b_\sigma (g_\sigma \sigma)^2,$$

with $g_\sigma \sigma$ in MeV. To test the sensitivity of our results to the $\sigma$ mass in the medium, the parameters were chosen [10]: ($a_\sigma$ ; $b_\sigma$) = (3.0, 5.0 and 7.5 $\times 10^{-4}$ MeV$^{-1}$ ; 10, 5 and 10 $\times 10^{-7}$ MeV$^{-2}$) for sets A, B and C, respectively. These values lead to a reduction of the $\sigma$ mass for sets A, B and C by about 2%, 7% and 10% respectively, at saturation density.
Using this parametrization for the $\sigma$ mass, the $\rho$-meson mass in matter is found to take quite a simple form (for $\rho_B \lesssim 3\rho_0$):

$$m^*_\rho \simeq m_\rho - \frac{2}{3}(g_\sigma\sigma)\left[1 - \frac{a_\rho}{2}(g_\sigma\sigma)\right],$$  \hspace{1cm} (2)

where $a_\rho \simeq 8.59, 8.58$ and $8.58 \times 10^{-4}$ (MeV$^{-1}$) for parameter sets A, B and C, respectively \(\dagger\).

For medium and heavy nuclei, it should be reasonable to use the MFA, and the mean-field values of all the meson fields at position $\vec{r}$ in a nucleus can be determined by (self-consistently) solving a set of coupled non-linear differential equations, generated from the QMC-II Lagrangian density \[10\]. We have calculated the $\rho$-meson mass in $^{12}$C in that way. However, for $^3$He and $^4$He, the MFA is not expected to be reliable. Therefore, we shall use a simple local-density approximation to calculate $m^*_\rho$ in helium.

In practice it is easy to parametrize the mean-field value of the $\sigma$ field calculated in QMC-II as a function of $\rho_B$ (see Fig.1 of Ref. \[10\]) and it is given as

$$g_\sigma\sigma \simeq s_1 x + s_2 x^2 + s_3 x^3,$$  \hspace{1cm} (3)

where $x = \rho_B/\rho_0$ and the parameters, $s_{1-3}$, are listed in Table \[\dagger\]. Therefore, once one knows the density distribution of the helium nucleus, one can easily calculate $g_\sigma\sigma$ at position $\vec{r}$ from Eq.(3), and then calculate $m^*_\rho(r)$ in the nucleus using Eq.(2).

In this paper we use a simple gaussian form for the density distribution of $^3$He, in which the width parameter, $\beta_3$, is fitted to reproduce the rms charge radius of $^3$He, 1.88 fm. For $^4$He, we parametrized the matter density as:

$$\rho_4(r) = A_4(1 + \alpha_4 r^2) \exp(-\beta_4 r^2),$$  \hspace{1cm} (4)

where $\alpha_4 = 1.34215$ (fm$^{-2}$) and $\beta_4 = 0.904919$ (fm$^{-2}$). This was chosen to reproduce the rms matter radius of $^4$He, 1.56 fm, and the measured central depression in the charge density.

Now we show our numerical results. In Figs. \[\dagger\]-\[3\] the density distributions and the $\rho$-meson masses in $^3$He, $^4$He and $^{12}$C are illustrated (for $^3$,$^4$He the density distribution is
common to all of the parameter sets, $A \sim C)$. The $\rho$-meson mass decreases by about 10 $\sim 15$ % at the center of the nucleus, although it depends a little on the parameter set chosen for the $\sigma$ mass variation.

We also show the average $\rho$-meson mass in the nucleus, which is defined as

$$\langle m^*_\rho \rangle_A = \frac{1}{A} \int d\vec{r} \rho_A(r)m^*_\rho(r),$$

where $\rho_A(r)$ is the density distribution of the nucleus A. The average mass is summarized in Table 2. In the present model the $\rho$-meson mass seems to be reduced by about 40 MeV in $^3$He, 80 MeV in $^4$He and 50 MeV in $^{12}$C, due to the nuclear medium effect. The larger shift in $^4$He is a consequence of the higher central density in this case.

It may be also very interesting to study the variation of the width of the $\rho$ meson in a nucleus. Unfortunately, since the present model does not involve the effect of the width, we cannot say anything about it. Asakawa and Ko [20], however, have reported on the mass and width of the $\rho$ meson although their calculations were carried out in nuclear matter. They have used a realistic spectral function, which was evaluated in the vector dominance model including the effect of the collisional broadening due to the $\pi$-N-$\Delta$-$\rho$ dynamics, on the hadronic side of the QCD sum rules, and concluded that the width of the $\rho$ meson decreases slightly as the density increases, which implies that the phase space suppression (from the $\rho \rightarrow 2\pi$ process) due to the reduction of the $\rho$-meson mass more or less balances the collisional broadening at finite density. Provided that the width of the $\rho$ meson is not significantly decreased by such medium corrections we may expect that the $\rho$ meson created by an external beam should decay inside the nucleus. This should lead to a clean signal of the variation of the $\rho$-meson mass [6].

In conclusion, we have calculated the $\rho$-meson mass in $^3$He, $^4$He and $^{12}$C using the QMC-II model, and found that it is reduced by about 10 $\sim 15$ % in those nuclei. It will be very interesting to compare our results with the experimental data taken at INS and currently being analysed [11].
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References

[1] K. Saito, T. Maruyama and K. Soutome, Phys. Rev. C40, 407 (1989).

[2] G.E. Brown and M. Rho, Phys. Rev. Lett. 66, 2720 (1991).

[3] T. Hatsuda and T. Kunihiro, Phys. Rep. 247, 221 (1994).

[4] K. Saito and A.W. Thomas, Phys. Rev. C51, 2757 (1995).

[5] K. Saito and A.W. Thomas, Phys. Rev. C52, 2789 (1995).

[6] T. Hatsuda, UTHEP-357 (Univ. of Tsukuba), nucl-th/9702002.

[7] M. Masera (HELIOS-3 collaboration), Nucl.Phys. A590, 93c (1995);
    Th. Ullrich (CERES collaboration), Nucl. Phys. A610, 317c (1996);
    E. Scomparin (NA50 collaboration), Nucl. Phys. A610, 331c (1996).

[8] M. Gonin (NA50 collaboration), Nucl. Phys. A610, 404c (1996).

[9] Quark Matter '96, Nucl. Phys. A610 (1996).

[10] K. Saito, K. Tsushima and A.W. Thomas, ADP-96-40/T236 (Univ. of Adelaide),
    nucl-th/9612001, to be published in Phys. Rev. C55, May (1997).

[11] INS-ES-134 and INS-ES-144, “Current experiments in elementary particle physics”,
    LBL-91 revised, UC-414, p.108 (1994);
    K. Maruyama, Proc. of the 25th Int. Symp. on Nuclear and Particle Physics with
    High-Intensity Proton Accelerators, Dec. 1996, Tokyo (Japan), to be published by
    World Scientific (Singapore), 1997.

[12] P.A.M. Guichon, K. Saito, E. Rodionov and A.W. Thomas, Nucl. Phys. A601, 349
    (1996);
    K. Saito, K. Tsushima and A.W. Thomas, Nucl. Phys. A609, 339 (1996),
    P.A.M. Guichon, K. Saito and A.W. Thomas, Australian Journal of Physics 50, 115
references are therein.

[13] P.A.M. Guichon, Phys. Lett. B200, 235 (1988).

[14] X. Jin and B.K. Jennings, Phys. Lett. B374, 13 (1996);
    Phys. Rev. C54, 1427 (1996);
    nucl-th/9606023, to be published in Phys. Rev. C55 (1997).

[15] P.G. Blunden and G.A. Miller, Phys. Rev. C54, 359 (1996).

[16] M. Jaminon and G. Ripka, Nucl. Phys. A564, 505 (1993);
    M.K. Banerjee and J.A. Tjon, nucl-th/9612007 (1996).

[17] A. Chodos, R.L. Jaffe, K. Johnson and C.B. Thorn, Phys. Rev. D10, 2599 (1974).

[18] V. Bernard and Ulf-G. Meissner, Nucl. Phys. A489, 647 (1988).

[19] J.C. Caillon and J. Labarsouque, Phys. Lett. B311, 19 (1993).

[20] M. Asakawa, C.M. Ko, P. Lévai and X.J. Qiu, Phys. Rev. C46, R1159 (1992);
    M. Asakawa and C.M. Ko, Phys. Rev. C48, R526 (1993).
Figure captions

Fig.1 Effective $\rho$-meson mass and the density distribution in $^3$He. The solid, dashed and dotted curves are, respectively, for the parameter sets A, B and C.

Fig.2 Same as for Fig.1 but for $^4$He.

Fig.3 Same as for Fig.1 but for $^{12}$C.
Figure 1:
Figure 2:
Figure 3:
Table 1: Three parameters for the mean-field value of $\sigma$ (in MeV).

| type | $s_1$ | $s_2$ | $s_3$ |
|------|-------|-------|-------|
| A    | 195.2 | −52.1 | 5.1   |
| B    | 214.0 | −44.3 | 1.9   |
| C    | 228.0 | −51.8 | 2.8   |
Table 2: Average $\rho$-meson mass (in MeV).

| type | $^3$He | $^4$He | $^{12}$C |
|------|--------|--------|---------|
| A    | 732    | 701    | 723     |
| B    | 727    | 691    | 718     |
| C    | 725    | 688    | 715     |