ρ-meson mass in light nuclei

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The quark-meson coupling (QMC) model is applied to a study of the mass of the ρ-meson in helium and carbon nuclei. The average mass of a ρ-meson formed in ^{3,4}He and ^{12}C is expected to be around 730, 690, and 720 MeV, respectively. [S0556-2813(97)04007-7]

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As the nuclear environment changes, hadron properties are nowadays expected to be modified [1–6]. 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/ψ 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 such as helium and carbon, an attempt to measure the ρ^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 [11,12]. They have measured ρ^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 ρ^0 production threshold. (Therefore, the $\pi^+\pi^-$ invariant mass spectrum that will be measured [11] corresponds to a ρ^0 meson that is almost at rest in the nucleus.) In view of this experimental work it is clearly very interesting to report on the variation of the ρ-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]). (In this paper we consider the rest mass in the medium.) 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. [13]. In this approach, which began with work by Guichon [14] in 1988, quarks in nonoverlapping nucleon bags interact *self-consistently* with scalar (σ) and vector (ω and ρ) mesons (the latter also being described by meson bags), in the mean-field approximation (MFA). Closely related investigations have been made in Refs. [15–17].

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 [18], 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_ω = 783 MeV and m_ρ = 770 MeV we introduce new z parameters for them, z_ω and z_ρ. 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_ω = 1.907, and z_ρ = 1.857 [10].

The model has several coupling constants to be determined: the σ-quark coupling constant g_σ^q and the ω-quark coupling constant g_ω^q are fixed to fit the binding energy (−15.7 MeV) at the correct saturation density (ρ_0=0.15 fm^{-3}) for symmetric nuclear matter. Furthermore, the ρ-quark coupling constant g_ρ^q is used to reproduce the bulk symmetry energy 35 MeV. Those values are listed in Tables I and III of Ref. [10].

Within QMC-II, the nonstrange 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 σ meson at that density [10]. However, the σ meson itself is not so readily represented by a simple quark model (such as a bag), because it couples strongly to the pseudoscalar (2π) channel and a direct treatment of chiral symmetry

TABLE I. Three parameters for the mean-field value of σ (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

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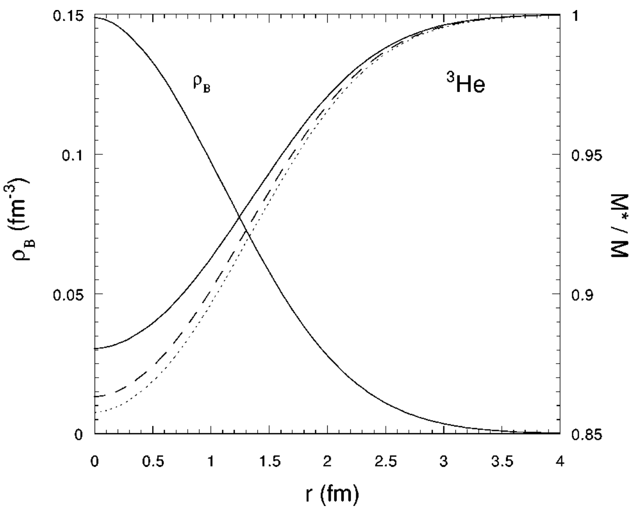

FIG. 1. Effective ρ-meson mass and the density distribution in ^{3}He. The solid, dashed, and dotted curves are, respectively, for the parameter sets A, B, and C.

in medium is important [3]. On the other hand, many approaches, including the Nambu–Jona-Lasinio model [3,19], the Walecka model [1,20] and Brown-Rho scaling [2] suggest that the σ-meson mass in medium $m_\sigma^\star$ should be less than the free value m_σ. We have parametrized it using a quadratic function of the scalar field:

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

with $g_\sigma\sigma$ in MeV. To test the sensitivity of our results to the σ mass in the medium, the following parameters were chosen [10]: (a_σ; b_σ) = (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 σ mass for sets A, B, and C by about 2, 7, and 10 %, respectively, at saturation density.

Using this parametrization for the σ mass, the ρ-meson mass (at rest) in matter is found to take quite a simple form (for $\rho_B \lesssim 3\rho_0$):

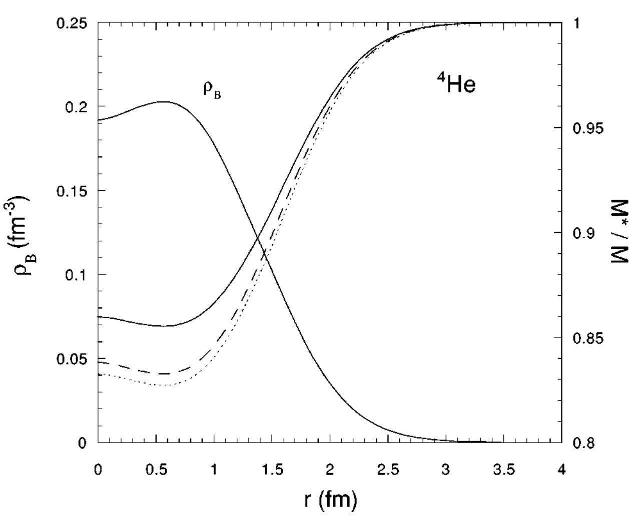

FIG. 2. Same as for Fig. 1 but for ^{4}He.

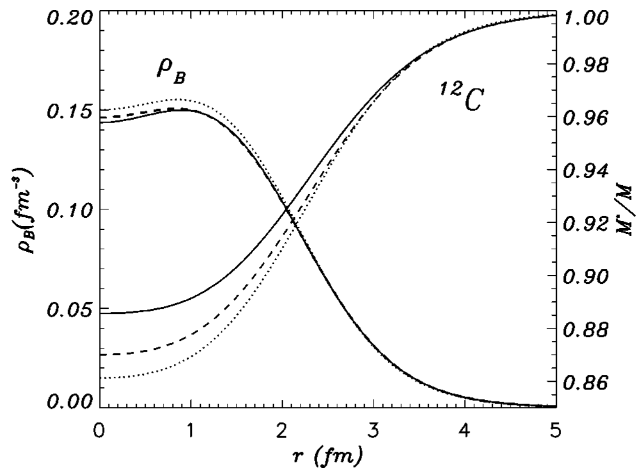

FIG. 3. Same as for Fig. 1 but for ^{12}C.

$$m_\rho^\star \simeq m_\rho - \frac{2}{3}(g_\sigma\sigma)\left[1 - \frac{a_\rho}{2}(g_\sigma\sigma)\right], \qquad (2)$$

where $a_\rho \simeq 8.59$, 8.58, and 8.58×10^{-4} (MeV^{-1}) for parameter sets A, B, and C, respectively [10]. We note that the splitting between the longitudinal and transverse masses of the vector meson is ignored because it is expected to be very small when the meson moves with low momentum [21].

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 nonlinear differential equations, generated from the QMC-II Lagrangian density [10]. We have calculated the ρ-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 $m_\rho^\star$ in helium.

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

$$g_\sigma\sigma \simeq s_1 x + s_2 x^2 + s_3 x^3, \qquad (3)$$

where $x = \rho_B/\rho_0$ and the parameters $s_{1\sim3}$ are listed in Table I. 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 $m_\rho^\star(r)$ 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 β_3 is fitted to reproduce the rms charge radius of ^{3}He, 1.88 fm. For ^{4}He, we parametrized the matter density as

$$\rho_4(r) = A_4(1 + \alpha_4 r^2)\exp(-\beta_4 r^2), \qquad (4)$$

where α_4 = 1.34215 (fm^{-2}) and β_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. 1–3, the density distributions and the ρ-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–C). The ρ-meson

TABLE II. Average ρ-meson mass (in MeV).

Type	^{3}He	^{4}He	^{12}C
A	732	701	723
B	727	691	718
C	725	688	715

mass decreases by about 10–15 % at the center of the nucleus, although it depends a little on the parameter set chosen for the σ mass variation.

We also show the average ρ-meson mass in the nucleus, which is defined as

$$\langle m_\rho^\star \rangle_A = \frac{1}{A} \int d\vec{r} \rho_A(r) m_\rho^\star(r), \quad (5)$$

where $\rho_A(r)$ is the density distribution of the nucleus A. The average mass is summarized in Table II. In the present model the ρ-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 also be very interesting to study the variation of the width of the ρ 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 [22], however, have reported on the mass and width of the ρ 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 π-N-Δ-ρ dynamics, on the hadronic side of the QCD sum rules, and concluded that the width of the ρ 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 ρ-meson mass more or less balances the collisional broadening at finite density. Provided that the width of the ρ meson is not significantly decreased by such medium corrections we may expect that the ρ meson created by an external beam should decay inside the nucleus. This should lead to a clean signal of the variation of the ρ-meson mass [6].

In conclusion, we have calculated the ρ-meson mass in ^{3}He, ^{4}He, and ^{12}C using the QMC-II model, and found that it is reduced by about 10–15 % in those nuclei. It will be very interesting to compare our results with the experimental data taken at INS and currently being analyzed [11], as well as the forthcoming experiments at TJNAF [12]. We do recognize that the present calculation is an estimate of this important effect, rather than a precision calculation. In particular, for the helium nuclei, it was necessary to use the local-density approximation to calculate the mass shift. This should be improved to obtain a more reliable prediction. (Note, however, that we were able to test the accuracy of the local-density approximation in ^{12}C, where it yielded results for the mass shift of the ρ within 10% of those obtained in the full calculation.) In actual experiments, a meson created in a nucleus will usually move with some finite momentum. In that case, it would be very interesting to look for the possible splitting between the longitudinal and transverse modes and the energy-momentum dependence of the mass in a nucleus [21,23].

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