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Behavior of the Λ(1405) resonance in nuclear matter*

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Strong interaction effects in kaonic atoms are heavily influenced by the properties of the subthreshold Λ(1405) resonance, which are here shown to be sizably modified by dynamic effects in nuclear matter. The present approach provides a simple view of an effect which is implicitly present in calculations which couple KN and $\Sigma\pi$ channels and incorporate a pion optical potential.

[NUCLEAR STRUCTURE Kaonic atoms, baryon resonances in nuclear matter.]

For some time, it has been known[1-3] that the hadronic properties[4] of kaonic atoms cannot be directly accounted for by a simple optical potential[5]

$$V_{KA} = -\frac{4\pi}{2m_{\rm red}} A\rho(\vec{r})\left(1+\frac{m_K}{M}\right) f_{KN}, \tag{1}$$

where m_K and M are the kaon and nucleon masses, $m_{\rm red}$ is the reduced mass for a system of a kaon and a nucleus of A nucleons with density $\rho(\vec{r})$ such that $\int \rho(\vec{r})d\vec{r} = 1$, and f_{KN} is the kaon-nucleon scattering amplitude at threshold (at 1432 MeV for the K^--p system, say). Indeed, Eq. (1) implies the opposite sign for ReV_{KA} from that seen experimentally,[6] and one must[1-3,7,8] take careful account of the Λ(1405) resonance, with $J^\pi = \frac{1}{2}^-$, $T = 0$, $\Gamma \cong 40$ MeV, which is only some 27 MeV below the K^-p threshold, in order to deal with this situation. It is the purpose of this comment to focus on a particular feature of the consequences of this resonance which tends to produce a reversal of the sign of ReV_{KA}. This effect is additional to those considered in Refs. 1 and 2, but is implicitly contained in Ref. 3; the present comment is thus intended to examine this aspect of kaonic atoms in isolation, and to provide a simple picture of it.

Some attention has been given[7] to modifications of the position and width of this resonance in nuclei—of obvious importance for the kaonic atom analysis—due to nucleon binding effects and the Pauli principle.[9,10] Relatively little effort has been made, however, explicitly to examine modifications of the resonance, for example, as arising from changes of pion propagation in the nuclear medium. An example of the effect in question is shown in Fig. 1; analogous effects for the Δ(1236) have been considered repeatedly in the past,[11-13] and the present work is close in spirit to those studies. One could of course consider similar corrections to the Σ propagator, but we have preferred to concentrate on the pion, which, for the physical Λ(1405) decay is very near to the kinematical region of the Δ(1236) resonance, and therefore involves an unusually large effect.

We consider the Λ(1405) self-energy (Fig. 1):

$$\Sigma_\Pi(E) = -\frac{iG^2}{\pi}\int d^4k \frac{1}{E - k_0 - M_\Sigma - k^2/2M_\Sigma + i\epsilon} \times \frac{1}{k^2+\mu^2-k_0{}^2+\Pi}\frac{1}{(k^2+\Lambda^2)^2}, \tag{2}$$

where G^2 is the effective coupling constant for the $\Lambda(1405) \to \Sigma\pi$ (s-wave) vertex as summed over intermediate spin-isospin states, M_Σ and μ are the Σ hyperon and pion masses, Π is the pion self-energy in the nuclear medium, and Λ is the cutoff parameter for the arbitrarily selected single pole vertex form used here. (One might suppose $\Lambda \sim 5\mu$ to 10μ in common with other more or less known meson-baryon cutoffs.) For the case of a free Λ(1405), the pion self-energy is merely replaced by the standard imaginary infinitesimal

$$\Pi \to -i\epsilon, \quad \epsilon \to 0^+, \tag{3}$$

and it is easy to verify that the Λ(1405) width is given by

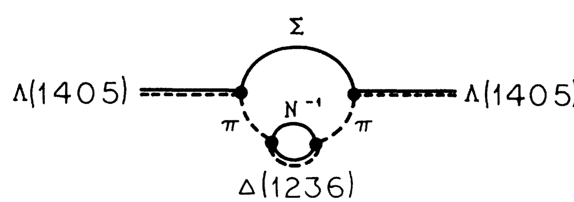

FIG. 1. Dynamic modification of the Λ(1405) resonance, arising from its virtual decay into a Σ hyperon and pion, the latter having its propagation modified by the creation of Δ(1236) πN resonance in the surrounding nuclear medium.

$$\Gamma = -2\,\mathrm{Im}\Sigma_{-i0^+} \quad (E = M_\Lambda)$$

$$= 8\pi^2 G^2 \frac{M_\Sigma}{M_\Sigma + (k^2+\mu^2)^{1/2}} \frac{k}{(k^2+\Lambda^2)^2}\bigg|_{k=k_\pi}, \qquad (4)$$

where k_π is determined from

$$M_\Lambda - (k_\pi^{\,2}+\mu^2)^{1/2} - M_\Sigma - \frac{k_\pi^{\,2}}{2M_\Sigma} = 0\,, \qquad (5)$$

which, with $M_\Lambda = 1405$ MeV and averaging on final charge states, yields $k_\pi = 148$ MeV/c. Equation (4) is to be viewed as evaluating the effective coupling constant G $[\cong 0.063(k_\pi^{\,2}+\Lambda^2)]$, which we here take to be unchanged in the medium.

Now, in the nuclear medium, we take the pion self-energy Π, appearing in the pion propagator, to be determined principally by the 3,3 resonance[12,13] as given by the theory of Chew and Low[14]:

$$\Pi(k,k_0) = -4\pi\rho \frac{k^2}{(1+k^2/\alpha^2)^2} \times \frac{\frac{4}{3}\lambda(k_0^{\mathrm{res}}/k_0)}{k_0^{\mathrm{res}} - k_0 - i\lambda(k_0^{\mathrm{res}}/k_0)(k_0^{\,2}-\mu^2)^{3/2}}\,, \qquad (6)$$

where ρ is the relevant nuclear matter density, $\lambda = \frac{4}{3}0.09/\mu^2$ is the effective πN coupling constant (squared) in the $j = t = \frac{3}{2}$ channel of the $\Delta(1236)$ resonance, $k_0^{\mathrm{res}} \approx 2.4\mu$ is the resonance position for laboratory variables as is approximately appropriate here, and $\alpha \approx 3.7\mu$ is the πN cutoff parameter.[15] Equation (2) will now imply a shift in the position of the resonance, which for the free case, or $\rho \to 0$ limit, determines a bare mass $M_\Lambda^{(0)}$ for the $\Lambda(1405)$ through

$$M_\Lambda^{(0)} + \mathrm{Re}\Sigma_{\Pi \to -i0^+}(M_\Lambda) = M_\Lambda\,, \qquad (7)$$

and for $\rho \neq 0$ yields a mass shift

$$\Delta \equiv \Sigma_\Pi(M_\Lambda) - \Sigma_{-i0^+}(M_\Lambda)\,. \qquad (8)$$

There is a corresponding change in the resonance width, as given by $\Gamma = -2\,\mathrm{Im}\Sigma_\Pi(M_\Lambda)$ without the limiting procedure of Eq. (3).

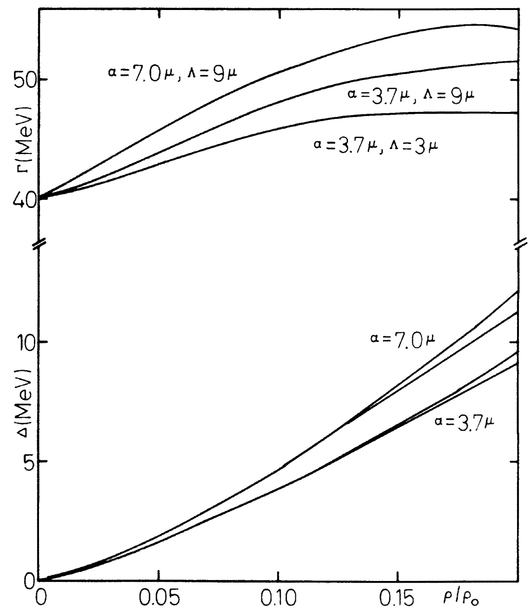

FIG. 2. The Λ resonance position shift Δ and width Γ, as functions of effective nuclear matter density ρ in units of the central density $\rho_0 \approx 0.16$ fm^{-3}. For kaonic atoms the relevant value is $\rho/\rho_0 \sim \frac{1}{8}$. Curves are shown for assumed values of the poorly known $\Lambda(1405) \to \Sigma\pi$ cutoff parameter Λ and for the πN range α, also uncertain; the upper shift curves are for $\Lambda = 9\mu$ and the lower for $\Lambda = 3\mu$. Note that these values of the shift Δ are to be compared with the 27-MeV separation of the $\Lambda(1405)$ free-space peak position and the K^-p threshold, indicating that the effect shown in Fig. 1 is of comparable importance to proton binding and to K^-p c.m. motion in the nuclear field in significantly reducing this gap.

It is convenient to reduce the evaluation of $\Sigma(E)$ of Eq. (2) to a single integration, and we therefore exploit the fact that the main contribution to the integrand comes from the region of the pion pole, and that near this region $\Pi(k,k_0)$ is reasonably slowly varying. We then perform the k_0 integration approximately, by contour methods, to obtain

$$\Sigma(E) \cong 4\pi G^2 \int_0^\infty \frac{k^2 dk}{[\omega_k^{\,2} + \Pi(k,\omega_k)]^{1/2}} \frac{1}{E - [\omega_k^{\,2}+\Pi(k,\omega_k)]^{1/2} - M_\Sigma - k^2/2M_\Sigma + i\epsilon} \frac{1}{(k^2+\Lambda^2)^2}, \qquad (9)$$

with $\omega_k \equiv (k^2+\mu^2)^{1/2}$. This is relatively easily evaluated numerically, with results for the changes in resonance position and width as shown in Fig. 2 as a function of effective nuclear density ρ. (Ordinary nuclear central densities $\rho_0 \approx 0.16$ fm^{-3} are not reached appreciably by the kaon bound in an atomic state—typically with fairly large orbital angular momentum—which instead is primarily affected[2] by densities $\rho/\rho_0 \sim \frac{1}{8}$.) These changes are fortunately not greatly modified by various assumptions concerning the $\Lambda(1405) \to \Sigma\pi$ cutoff parameter, as seen in Fig. 2, although they are somewhat affected by the πN cutoff α, also not well determined. The shift Δ is to be compared with the 27-MeV gap which separates the $\Lambda(1405)$ peak position from K^-p threshold, a gap which is reduced in nuclei by some[2] 10 to 30 MeV due to the combined effects of the binding of the proton and the center-of-mass motion of the K^-p subsystem in the nuclear field. The upward shift in the position of the resonance arising from virtual pion interactions in the nuclear medium is thus comparable to either of the latter two effects. When included in kaonic atom optical potentials, as done implicitly in Refs. 3 and 8, it will work in the same direction as the two kinematic effects; that is to say, it will further enhance the desired reversal in sign of the real part of the potential.

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