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Relativistic mean field theory and hypernuclei

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The success of the relativistic mean field theory (RMFT) in describing nuclear structure and dynamics[1] has quite naturally inspired attempts to apply the theory to a more general baryon-nucleus interactions. A consistent description of both nuclear and hypernuclear systems has been obtained[2,3] and is regarded as a significant achievement of the RMFT.

In this work, we perform the first fully selfconsistent calculations of Λ , Σ and Ξ hypernuclei including the ωYY anomalous coupling. Our main aim is to discuss the couplings of hyperons to different mesonic fields and the implications for hypernuclear spectroscopy.

The formalism is based on the Lagrangian density of the form

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_Y, \quad Y = \Lambda, \Sigma, \Xi,$$

$$\mathcal{L}_Y = \bar{\Psi}_Y [i\gamma_\mu \partial^\mu - g_{\omega Y} \gamma_\mu V^\mu - (M_Y + g_{\sigma Y} \phi)] \Psi_Y + \mathcal{L}_{\rho Y} + \mathcal{L}_{AY} + \mathcal{L}_T,$$

$$\mathcal{L}_T = \frac{f_{\omega Y}}{2M_Y} \bar{\Psi}_Y \sigma^{\mu\nu} \partial_\nu V_\mu \Psi_Y.$$

Here, $\mathcal{L}_N$ is the standard nuclear Lagrangian[1], $\mathcal{L}_{\rho Y}$ and $\mathcal{L}_{AY}$ describe interactions of a hyperon with the ρ meson and Coulomb field, respectively. Finally, the $\mathcal{L}_T$ is the ωYY anomalous coupling term. This term is crucial in order to get a negligible Λ spin orbit splitting for the larger values of the Λ couplings required by constituent quark model.

The system of coupled field equations for both baryons (N , Y) and meson fields ϕ , V_0 , b_0 , A_0 results from $\mathcal{L}$ using standard techniques and approximations.[1,3]

For the coupling of the ω and ρ mesons to the hyperons we have used the naive quark model values.[4] The $g_{\sigma Y}$ coupling was fitted so as to reproduce the hyperon binding in nuclear matter. We have neglected the hyperon conversion and charge exchange effects.

The RMFT model introduced here gives reasonable description of hypernuclear characteristics – hyperon binding in nuclear matter, spin orbit interaction, single particle energies. We have witnessed large effects from the ρ – hyperon interaction in Σ and Ξ hypernuclei. In Zr and Pb the ρ contribution tends to compensate the effect of the Coulomb potential. In particular, the binding B_{Σ^+} converts from decreasing to an increasing function of A in the systems with a neutron excess. The self-consistent calculations revealed slightly attractive ρ contribution even in hypernuclei with $N \approx Z$ (O , Ca).

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The tensor coupling is critical for evaluating the hypernuclear spin orbit interaction. In Figure 1, 4_YCa ($Y = \Lambda, \Sigma^0, \Xi^0$) calculated using various tensor couplings $\alpha_{TY} = f_{\omega Y}/g_{\omega Y}$ illustrates quite different evolution of the spin orbit splitting for three kinds of hyperons. The quark model values of $f_{\omega Y}$ (underlined in Fig. 1) for Λ , Σ and Ξ differ in sizes and signs. As a consequence, the spin orbit interaction for Λ nearly vanishes, it is almost doubled for Σ , and changes sign for Ξ .

Although the effect of tensor coupling is relatively large, the absolute shifts in energy levels amount to less than 1 MeV and this is probably still beyond current experimental resolution.[5]

However, recent activities in facilities with hypernuclear program – BNL, CEBAF, KEK – suggest new perspectives of the hypernuclear spectroscopy in this decade.

Figure 1. Dependence of the hyperon single particle levels in 4_YCa ($Y = \Lambda, \Sigma^0, \Xi^0$) on the $\alpha_{TY} = f_{\omega Y}/g_{\omega Y}$.

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