Chiral Sigma Model with Pion Mean Field in Finite Nuclei

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The theoretical framework to treat explicitly the pion mean field in finite nuclei has been developed by introducing the parity mixed intrinsic single particle states[1]. The purpose of this work is to study the properties of finite nuclei and the role of the pion using chiral sigma model within the relativistic mean field theory. Chiral symmetry is known to be the most important symmetry in hadron physics, which is described nicely in the linear sigma model[2]. The pion, which was introduced by Yukawa as the mediator of the nuclear force[3], received its foundation through the spontaneous chiral symmetry breaking[4]. We then try to understand the nuclei based on the fundamental symmetry in hadron physics. We employ the sigma model Lagrangian in the non-linear realization. In order to treat the pion in the Hartree level, we use the non-linear version to avoid the serious treatment of the negative energy states comes from the pseudoscalar coupling. The extended chiral sigma(ECS) model Lagrangian is given as follows,

$$\begin{aligned} \mathcal{L}'_{\sigma\omega} &= \bar{\psi}(i\gamma_\mu\partial^\mu - M - g_\sigma\sigma - \frac{g_A}{2f_\pi}\gamma_5\gamma_\mu\vec{\tau}\cdot\partial^\mu\vec{\pi} - g_\omega\gamma_\mu\omega^\mu)\psi \\ &+ \frac{1}{2}\partial_\mu\vec{\pi}\partial^\mu\vec{\pi} - \frac{1}{2}{m_\pi}^2\vec{\pi}^2 + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}{m_\sigma}^2\sigma^2 - \lambda f_\pi\sigma^3 - \frac{\lambda}{4}\sigma^4 \\ &- \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}{m_\omega}^2\omega_\mu\omega^\mu + \widetilde{g_\omega}^2 f_\pi\sigma\omega_\mu\omega^\mu + \frac{1}{2}\widetilde{g_\omega}^2\sigma^2\omega_\mu\omega^\mu, \end{aligned} \tag{1}$$

where the vacuum expectation value of the scalar meson is taken as the pion decay rate, f_π. The nucleon and omega meson masses are generated dynamically by the sigma condensation in the vacuum as $M = g_\sigma f_\pi$ and $m_\omega = \widetilde{g_\omega} f_\pi$[5], respectively. The following masses and the pion decay rate are fixed from the hadron properties in free space as, $M = 939$ MeV, $m_\omega = 783$ MeV, $m_\pi = 139$ MeV, and $f_\pi = 93$ MeV. Two parameters m_σ and g_ω are fixed as $m_\sigma = 777$ MeV and $g_\omega = 7.033$ to reporduce the saturation properties for nuclear matter, which are the density, $\rho = 0.141$ fm^{-3}, and the energy per particle, $E/A = -16.1$ MeV. The incompressibility in this case, however, comes out to be too large, $K = 650$ MeV. Another characteristic property of this model is that the scalar and vector potentials, which are related with the strength of spin-orbit interaction, are about a half of the case of the standard RMF calculation with the TM1 parameter set[6] in nuclear matter.

We applied this model for finite nuclei (N = Z even-enen mass from N = 16 up to 34). We solved the coupled equations for nucleon and mesons by doing iterative calculations[1]. The same parameters are used as those of the nuclear matter except for $g_\omega = 7.176$ instead of 7.033 and $g_A = 1.15$ for overall agreement with the RMF(TM1) results. The result is shown in Fig. 1. The ECS model without the pion mean field gives the result that the magic number appears at N = 18 instead of N = 20. This result comes from the large incompressibility in nuclear matter. This property leads to the $1s$-orbit pushed up anomalously. We note that this problem originates from the ECS model treated in the present framework. We expect to remove this problem in the future work.

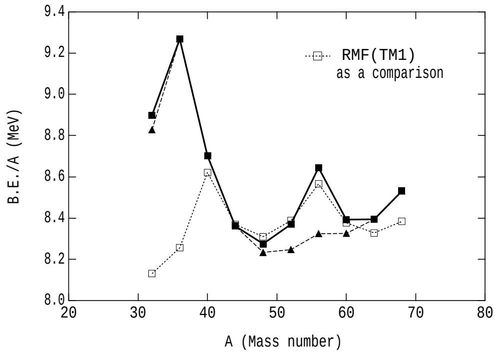

Figure 1: The binding energies per particle given by the ECS model with(solid) and without(dashed) the pion mean field.

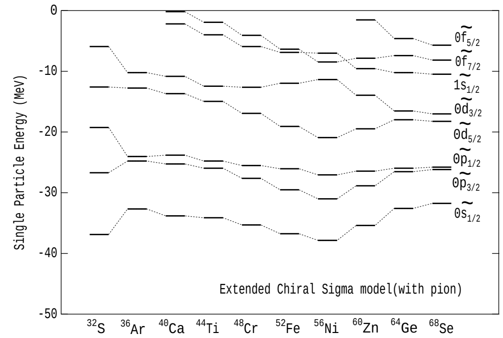

Figure 2: The proton single particle spectra for the ECS model with the pion mean field. The dominant angular momentum states are written.

The second result is that the magic number does not appear at N = 28. This result comes from another characteristic property of this model, which leads to the small spin-orbit interaction. The energy splittings between the spin-orbit partners are small and have no response to produce the magic effect at N = 28. As for this point, it is very important to introduce the pion mean field. The pionic correlations due to the finite pion mean field are expressed by the coherent 0^- particle-hole excitations[1], in which the coupling of the different parity levels l and $l' = l \pm 1$ with the same total spin j in the shell model language. In this mechanism only the highest j spin level does not find the partner in the lower major shells. If once nucleons start to occupy in this level, those nucleons are able to find the partners in the higher major shells. The highest spin level is the $f_{7/2}$ in this mass region and the nucleons in this level are used for the 0^- particle-hole excitations into $g_{7/2}$. The number of particles to be used by the pionic correlation increases, as the nucleon number in $f_{7/2}$ level is increased until ^{56}Ni, where the $f_{7/2}$ state is completely occupied. For the nuclei above ^{56}Ni, the upper shells as $f_{5/2}$ are to be occupied and those states are not used from the $d_{5/2}$ state due to the Pauli blocking. The pionic correlation becomes maximum at ^{56}Ni. This is the reason why ^{56}Ni obtains largest pionic correlation energy, which leads to the appearance of the magic effect at N = 28. Figure 2 shows the single particle spectra. Due to the pionic correlation, the parity partners as ($s_{1/2}$ and $p_{1/2}$), ($p_{3/2}$ and $d_{3/2}$) and ($d_{5/2}$ and $f_{5/2}$) are pushed out each other and as the consequence that the spin-orbit partners are split largely like the ones of the ordinary spin-orbit splittings.

The chiral sigma model is able to provide the nuclear property with only a small adjustment of the parameters in the Lagrangian. The energy splitting between spin-orbit partners is caused by the pionic correlation which is completely a different mechanism from the case of the spin-orbit interaction introduced phenomenologically.

References

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