Relativistic Mean Field Theory with the Pion for Finite Nuclei

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We have developed a mean-field model that incorporates the pion. It is based on the relativistic mean field (RMF) theory. We applied the new model to various N=Z nuclei and found that the pion has a large effect on the nuclear mean field.

Recently, mean-field models, relativistic or non-relativistic, are widely used to study nuclear structure. They can reproduce the saturation property of nuclei and the properly large spin-orbit splittings, and therefore give results that agree with the experimental data, especially bulk data. In these models the tensor force from the pion exchange is usually missing. However, we know that the tensor force plays an important role in nuclear structure based on many studies. For example, a half of attraction is gained by the tensor force in a alpha nucleus [1] and recent *ab initio* calculation for few-body systems show that the force has large effect on them. For medium and heavy mass region, the quenching of Gamow-Teller strength is explained by the mixing of higher order configurations to the one-particle–one hole state of a simple Gamow-Teller transition. The mixing is caused by the residual interaction and, in this case, the contribution of the tensor force is comparable to the central force. [2] Therefore, it is interesting to study the nuclear structure in a relativistic mean-field framework with the pion.

In the relativistic mean field theory, we make the mean field approximation (the Hartree approximation). In this approximation, because the pion is a pseudoscalar meson, the expectation value of the pion field should be zero if we assume parity symmetry of single-particle states in a mean field. This is the reason why we did not include the pion in the RMF theory. However, if we imagine that single-particle-states in the mean field are not good parity states, namely, mixed-parity states, the situation drastically changes. In this case, the pion can be exchanged by those states because there exist parity partners in themselves. As a result, the expectation value of the pion field becomes finite. The total wave function made by the mixed-parity states is not a good parity state, and therefore we need to project out the good parity state from it. In this way, we can obtain a wave function that includes the correlation caused by the pion.

The Lagrangian which we use is

$$\begin{aligned} \mathcal{L} &= \bar{\psi}\Big(i\gamma_\mu\partial^\mu - M - g_\sigma\sigma - g_\omega\gamma_\mu\omega^\mu - \frac{f_\pi}{m_\pi}\gamma^5\gamma_\mu\tau^a\partial^\mu\pi^a\Big)\psi \\ &\quad +\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu \\ &\quad +\frac{1}{2}\partial_\mu\pi^a\partial^\mu\pi^a - \frac{1}{2}m_\pi^2\pi^a\pi^a. \end{aligned} \tag{1}$$

In the above equation, only linear terms are written, but in the actual calculation the nonlinear terms of the sigma and omega mesons are included. For the coupling constants and masses for mesons, except for the pion, we use the TM1 parameter set. [3] For the pion-nucleon coupling we adopt the pseudovector type and set the value to $f_\pi \approx 1$, which is taken from the Bonn A potential. [4] Because the TM1 parameter set is determined in the absence of the pion, the effect of the pion is included in the other mesons. Therefore, we should refit the parameters in the presence of the pion. This is our next task.

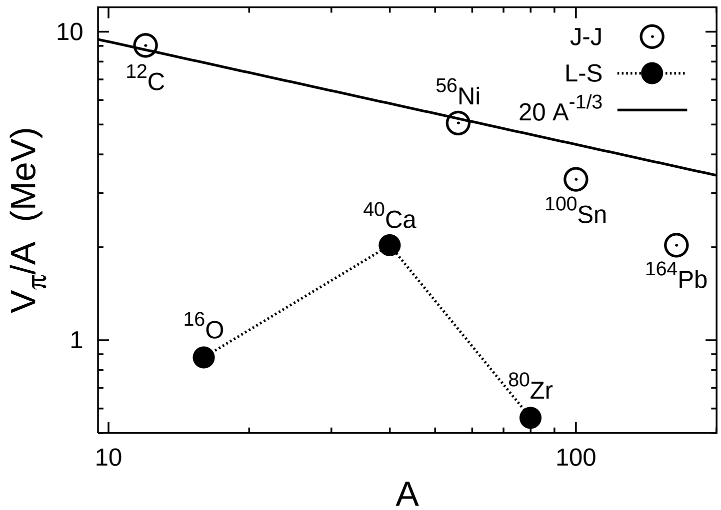

Figure 1: Pion energy per nucleon as a function of the mass number in a log-log plot. [5] There are two groups: one is for the jj-closed shell nuclei, denoted by the open circles, the other is for the LS-closed shell nuclei, denoted by the solid circles. The pion energy per nucleon for the jj-closed shell nuclei decreases monotonically and follows a steeper curve than $A^{-1/3}$, which is shown by the solid line.

In Fig. 1 we show the potential energy of the pion normalized by mass numbers. [5] From this figure we can see that the pion energies do not behave volume-like and make a large contribution to the binding energies (about 5 MeV per nucleon for ^{56}Ni).

We have just started a study of the pion in a relativistic mean-field model. Thus, our result is not very quantitative. We need to significantly modify our model. However, we believe that through this study we can obtain a new understanding of how the pion behaves in nuclei.

References

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