Chiral Physics in Mesic Atoms and Mesic Nuclei

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We summarize recent research activities on the mesic atoms and mesic nuclei in the context of the chiral dynamics in medium. We briefly introduce the studies of Kaon-, \( \eta \)-, \( \eta' \)(958)-bound states in nuclei.

§1. Introduction and motivation

In the contemporary hadron physics, the light pseudoscalar mesons \((\pi, K, \eta)\) are recognized as the Nambu-Goldstone bosons associated with the spontaneous breaking of the QCD chiral symmetry. In real world, these mesons, together with heavier \( \eta' \)(958) meson, show the involved mass spectrum, which are believed to be explained by the explicit flavor \( SU(3) \) breaking due to current quark masses and the breaking of the axial \( UA(1) \) symmetry at the quantum level referred as the \( UA(1) \) anomaly.\(^1\),\(^2\) One of the most important subjects in hadron physics at present is to reveal the origin of the hadron mass spectra and to find out the quantitative description of hadron physics from QCD.\(^3\)

Recently, there are several very important developments for the studies of the spontaneous breaking of chiral symmetry and its partial restoration at finite density. To obtain deeper insights on the in-medium behavior of spontaneous chiral symmetry breaking, the hadronic systems, such as pionic atoms,\(^4\)–\(^6\) \( \eta \)-mesic nuclei\(^7\)–\(^10\) and \( \omega \)-mesic nuclei,\(^7\),\(^8\),\(^11\)–\(^13\) have been investigated in both of theoretical and experimental aspects. Especially, after a series of deeply bound pionic atom experiments,\(^14\),\(^15\) Suzuki et al. reported the quantitative determination of pion decay constant \( f_\pi \) in medium from the deeply bound pionic states in Sn isotopes\(^5\),\(^16\) and stimulated many active researches of the partial restoration of chiral symmetry at finite density.\(^4\),\(^6\),\(^17\)–\(^19\)

In this paper, we summarize the current interests of the chiral dynamics in mesic atoms and mesic nuclei.

§2. Missing mass spectroscopy

The standard method to produce mesic atoms starts with injecting slow negative mesons into matter; the mesons will be stopped and trapped in outermost orbits of atoms, then lose energy by emitting Auge electrons and x-rays to cascade down to deeper atomic states. The binding energies and widths of the mesic bound states provide us with a unique information of the meson-nucleus interaction.\(^20\)

However, the x-ray cascade ceases at the so-called ‘last orbital’, where the mesons are absorbed by the nucleus without going into deeper atomic states. This prevents

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us from studying the deep mesic states that have large overlap with nuclear density.\textsuperscript{21)}

To overcome this difficulty, the recoilless meson production by the \((d,^3\text{He})\) has been proposed;\textsuperscript{22)} this method tries to directly create deeply bound pions by the nuclear reaction without the cascade down of the pion from the outermost orbits. This direct method was proved to be effective and powerful for the study of far deeply bound pionic atoms:\textsuperscript{5), 14)–16)} we can now determine the binding energies and widths of the deepest bound states such as 1s and 2p atomic states from the energy spectra of the emitted \(^3\text{He}\). We remark that the \((d,^3\text{He})\) reaction is so powerful that it may be applied to the creation of even neutral meson-nucleus bound states such as \(\eta\) and \(\omega\) mesic nuclei.\textsuperscript{7), 8), 11)} And after the success of the missing mass spectroscopy of the pionic atoms by the \((d,^3\text{He})\) reactions, other reactions such as \((\gamma,p)\),\textsuperscript{23)–25)} \((\bar{K},N)\),\textsuperscript{26)–29)} etc. were also considered to observe the meson-nuclear systems.

\section*{3. Kaonic atoms and kaonic nuclei}

The \(K^-\)-nucleus interaction has been studied for a long time based on the kaonic atom data obtained by the X-ray spectroscopy. In Ref. \textsuperscript{30)}, the phenomenological studies of kaonic atoms are performed comprehensively, where the density-dependent potentials are considered for \(\chi^2\) fitting to take into account possible non-linear effects which could be due to \(\Lambda(1405)\) resonance. There are also \(K^-\)-nucleus theoretical interactions based on the SU(3) chiral Lagrangian.\textsuperscript{31)–37)} These theoretical potentials are shown to have the ability to reproduce the kaonic atom data reasonably well.\textsuperscript{38), 39)} The kaonic nuclear states were also studied using these interactions and shown to have large decay widths of the order of several tens of MeV.\textsuperscript{38), 40), 41)}

In recent years, there have been many researches in the studies of kaonic nuclear states, which are kaon-nucleus bound systems by the strong interaction inside the nucleus. Experimental studies of the kaonic nuclear states using in-flight \((\bar{K},N)\) reactions were proposed and performed by Kishimoto and his collaborators.\textsuperscript{28), 29)} And the theoretical results of the energy spectra of the in-flight \((\bar{K},N)\) reaction were obtained in Ref. \textsuperscript{26)} and later in Ref. \textsuperscript{27)} with the Green function method, where we have shown the difficulties to obtain clear signals for kaonic nuclear states formation experimentally. Similar results were also reported in Ref. \textsuperscript{42)}. On the other hand, indications of \(K^- pp\) bound state were reported by the FINUDA experiment.\textsuperscript{43)} There are also theoretical studies of the structure and formation of kaonic nuclear states related to these experimental activities.\textsuperscript{44)} It should be noted that these theoretical studies predict the possible existence of ultra-high density states in kaonic nuclear systems.\textsuperscript{44), 45)} The existence of the high density states is considered to be closely related to the short range core of the nucleon-nucleon potential and the high density state could not be observed in the theoretical calculation with the realistic core potential.\textsuperscript{46)} The critical analyses of the latest data were also reported by Oset and Toki and their collaborators.\textsuperscript{47), 48)} In our previous papers,\textsuperscript{26), 27)} we have made clear that the signals of the kaonic nuclear state formation in the \((\bar{K},N)\) reactions are expected to be very small. These could be complementary results to those of Oset and Toki who claimed that the origins of the structure in the experimental spectra
can be explained by the well-known processes.\textsuperscript{47, 48} The detailed analysis was also performed to understand fully the FINUDA data.\textsuperscript{49} We also mention here that some indications of existence of the NARROW kaonic nuclear states reported in Ref. 50) were withdrawn by the authors in recent conference talks.\textsuperscript{51}

One of the most important physical effects to realize the NARROW kaonic nuclear states assumed in Refs. 28), 44) and 45) is the suppression of the imaginary potential for deeply bound kaonic nuclear states due to the threshold effects of the decay processes. Actually the one-body process $\bar{K}N \rightarrow \pi \Sigma$ does not occur if the total energy is smaller than the threshold energy $E = m_{\bar{K}} + m_N - 101$ MeV, and as for the two-body process $\bar{K}NN \rightarrow \Sigma N$, the threshold energy is $E = m_{\bar{K}} + 2m_N - 239$ MeV, where we have used the average masses of their charged states for $\pi$, $N$, $\Sigma$ hadrons. Thus, if the $\bar{K}$ has much smaller energies in the nucleus than that in vacuum, these decay channels could be suppressed by the threshold effects. In the bound states of some of the kaonic nuclear states predicted in Refs. 44) and 45), the one-body decay processes could be closed. However, the two-body processes are still open at those energies and provide the imaginary part of the kaon-nucleus potential, which can be expected to have larger effects than one-body processes for higher nuclear densities such as predicted in Refs. 44) and 45). Thus, we think that it is very important to know correctly the strength of one-body and two-body decay channels for the studies of the kaonic nuclear states.

For the kaonic atoms and kaonic nuclei, first we have studied theoretically the kaonic atom and kaonic nucleus formations in the in-flight $(K^-, p)$ reactions\textsuperscript{26), 27) using the Green function method, which is suited to evaluate formation rates both of stable and unstable bound systems, as reported in Ref. 27). We have considered $^{12}$C and $^{16}$O as the targets and calculate the spectra of the $(K^-, p)$ reactions. We conclude that no peak structure due to kaonic nucleus formation is expected in the reaction spectra calculated with the chiral unitary kaon-nucleus optical potential.\textsuperscript{31)} In the spectra with the phenomenological deep kaon-nucleus potential,\textsuperscript{30) we may have possibilities to observe some structures due to the formation of the kaonic nucleus states. For all cases we considered in Refs. 26) and 27), we find clear signals due to the kaonic ATOM formations in the reaction spectra, which show the very interesting structures like the ‘resonance dip’ instead of the ‘resonance peak’ for the atomic $1s$ state formation.

We have then considered the kaon absorption from atomic states into nucleus in detail in Ref. 52). We found that the nuclear density probed by the atomic kaon significantly depends on the kaon orbit. Then, we reexamined the meanings of the observed strengths of one-body and two-body kaon absorption, and investigated the effects to the formation spectra of kaon bound states by in-flight $(K^-, p)$ reactions. As a natural consequence, if the atomic kaon probes the smaller nuclear density, the ratio of the two-body absorption at nuclear center is larger than the observed value in kaonic atoms, and the depth of the imaginary potential is deeper even at smaller kaon energies as in kaonic nuclear states because of the large phase space for the two-body processes.\textsuperscript{52)} This deeper imaginary potential makes the signals of kaonic nucleus formation more unclear in the $(K^-, p)$ spectra.
§4. η mesic nuclei

In this section, we discuss the η-nucleus system. The η-mesic nuclei were studied by Haider and Liu\(^5\)\(^3\) and by Chiang, Oset and Liu\(^5\)\(^4\).\(^\) As for the formation reaction, the attempt to find the bound states by the \((\pi^+, p)\) reaction led to a negative result.\(^5\)\(^5\)\(^\) Recently, some experiments in photoproduction processes indicated observations of such bound states in \(^{12}\)C target\(^5\)\(^6\) and \(^{3}\)He target\(^5\)\(^7\) and another experiment is now planned to investigate the η-nucleus interaction.\(^8\) In our study we use the same theoretical models for η-nucleus interaction, as described in Refs. 24) and 9) in further detail, to investigate the structure and formation of the η mesic nuclei. We briefly introduce the concepts of our theoretical models here.

In the η-nucleon system, the \(N(1535)\) resonance (\(N^*\)) plays an important role due to the dominant ηNN\(^*\) coupling. We evaluate the η-nucleus optical potential \(V_\eta(\omega, \rho(r))\) in the two different models which are based on distinct physical pictures of \(N^*\). One is the chiral doublet model. This is an extension of the linear sigma model for the nucleon and its chiral partner.\(^5\)\(^8\)–\(^6\)\(^0\) The other is the chiral unitary model, in which \(N^*\) is dynamically generated in the coupled channel meson-baryon scattering.\(^1\)\(^0\), \(^6\)\(^1\)

In the first approach, the \(N^*\) is introduced as a particle with a large width and appears in an effective Lagrangian together with the nucleon field. Assuming \(N^*\)-hole excitation induced by the η meson in nucleus, we obtain the η-nucleus optical potential at finite nuclear density as

\[
V_\eta(\omega, \rho(r)) = \frac{g_\eta^2}{2\mu} \frac{\rho(r)}{\omega + m_N^*(\rho) - m_{N^*}(\rho) + i\Gamma_{N^*}(\omega, \rho)/2},\]

in the local density approximation and the heavy baryon limit.\(^5\)\(^4\) Here \(\mu\) is the η-nucleus reduced mass and \(\rho(r)\) is the density distribution of the nucleus. The ηNN\(^*\) coupling is assumed to be S-wave:

\[
\mathcal{L}_{\eta NN^*}(x) = g_\eta \bar{N}(x)\eta(x)N^*(x) + H.c.,
\]

and the coupling constant \(g_\eta\) is determined to be \(g_\eta \approx 2.0\) in order to reproduce the partial width \(\Gamma_{N^*-\eta N} \approx 75\) MeV at tree level. The S-wave nature of the ηNN\(^*\) vertex simplifies the particle-hole loop integral in Eq. (4.1). \(m_N^*\) and \(m_{N^*}^*\) are the effective masses of \(N\) and \(N^*\) in the nuclear medium, respectively. Considering that the \(N^*\) mass in free space lies only 50 MeV above the threshold and that the mass difference of \(N\) and \(N^*\) might change in the medium, the η-nucleus optical potential is expected to be extremely sensitive to the in-medium properties of \(N\) and \(N^*\). For instance, if the mass difference reduces in the nuclear medium as \(m_\eta + m_N^* - m_{N^*}^* > 0\), then the optical potential turns to be repulsive.\(^9\) As we shall see in Ref. 9), in the chiral doublet scenario of \(N\) and \(N^*\), the repulsive η-nucleus interaction can be realized in the nuclear medium due to the symmetry restoration. This exotic behavior of the η-nucleus interaction is independent of the absolute value of \(a_\eta\) in our model.

In the chiral doublet model together with the assumption of partial restoration of chiral symmetry, a reduction of the mass difference of \(N\) and \(N^*\) in the medium
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is found to be in the mean field approximation as

\[ m_N^*(\rho) - m_{N^*}^*(\rho) = \Phi(\rho)(m_N - m_{N^*}), \] (4.3)

where \( m_N \) and \( m_{N^*} \) are the \( N \) and \( N^* \) masses in free space, respectively, and

\[ \Phi(\rho) = 1 - C \frac{\rho}{\rho_0}. \] (4.4)

Here we take the linear density approximation of the in-medium modification of the chiral condensate, and the parameter \( C \) represents the strength of the chiral restoration at the nuclear saturation density \( \rho_0 \). The empirical value of \( C \) lies from 0.1 to 0.3.\(^{64}\)

Let us move on the second approach of the chiral unitary model.\(^{10,61}\) In this approach, the \( N^* \) resonance is expressed as a dynamically generated object in the meson baryon scattering, and one solves a coupled channel Bethe-Salpeter equation to obtain the \( \eta \)-nucleon scattering amplitude. The optical potential in medium is obtained by closing the nucleon external lines in the \( \eta N \) scattering amplitude and considering the in-medium effect on the scattering amplitude, such as Pauli blocking. Since the \( N^* \) in the chiral unitary approach is found to have a large component of \( K \Sigma \) and the \( \Sigma \) hyperon is free from the Pauli blocking in nuclear medium, very little mass shift of \( N^* \) is expected in the medium,\(^{65}\) while the chiral doublet model predicts the significant mass reduction as discussed above.

The optical potentials and the calculated formation spectra show much different behaviors for these two models as shown in Refs. 9) and 24). In addition, as described in the next section, we can consider the quark degrees of freedom to study the \( \eta \) meson in nuclear medium. Thus, it should be interesting and important to observe the spectra in experiments and to distinguish the theoretical models which have much different pictures for the structure of \( N(1535) \).

§5. \( \eta \) and \( \eta'(958) \) mesic nuclei in NJL model

The present exploratory level is rather poor for the behavior of the \( U_A(1) \) anomaly in the nuclear medium. Although some theoretical results have been reported, there exists no experimental information on the possible effective restoration of the \( U_A(1) \) anomaly at finite density. Kunihiro studied the effects of the \( U_A(1) \) anomaly on \( \eta' \) properties at finite temperature using the Nambu-Jona-Lasinio model\(^{66}\) with the KMT term,\(^{67,68}\) which accounts for the \( U_A(1) \) anomaly effect, and showed the possible character changes of \( \eta' \) at \( T \neq 0 \). There is another theoretical work with a linear \( \sigma \) model.\(^{69}\) Theoretical predictions by other authors also reported the similar consequences\(^{70,71}\) and supported the possible change of the \( \eta' \) properties at finite density as well as at finite temperature.

Thus, we propose the formation reaction of the \( \eta' \)-mesic nuclei and discuss the possibility to produce the \( \eta' \)-nucleus bound states in order to investigate the \( \eta' \) properties, especially mass shift, at finite density.\(^{72,73}\) Since the huge \( \eta' \) mass is believed to have very close connection to the \( U_A(1) \) anomaly, the \( \eta' \) mass in the
medium should provide us important information on the effective restoration of the \( U_A(1) \) symmetry in the nuclear medium.\(^{72,74}\)

In Ref. 73), we consider the \( \eta \) and \( \eta' \) meson properties in atomic nuclei and the structures of the \( \eta \)- and \( \eta' \)-mesic nuclei using the \( SU(3)_f \) NJL model\(^{75}\) in order to get much deeper insights on the \( \eta' \) mass shifts and their relation to \( U_A(1) \) anomaly effects than our first work shown in Ref. 72). The low-lying meson properties have been studied\(^{1},2),76,77,78,79\) using the three-flavor version of the Nambu-Jona-Lasinio (NJL) model\(^{75}\) with the Kobayashi-Maskawa-'t Hooft (KMT) determinant interaction.\(^{67,68}\) We also propose the formation reaction of the \( \eta \)- and \( \eta' \)-mesic nuclei and discuss the possibility to produce the \( \eta \)- and \( \eta' \)-nucleus bound states.\(^{72,73}\)

§6. Summary

We summarized the current status and interests of mesic atoms and mesic nuclei in relation to the chiral dynamics in nuclear medium. We believe meson-nucleus bound systems are fruitful to investigate meson properties in nuclear medium and to get new information on symmetry restoration at finite density.

We also think that the realistic calculations of the structure and formation spectra are necessary for all observed results to study the meson properties in nuclear medium, and to get the decisive conclusions.

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