Advanced Meson Science Laboratory – Hadron part –

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The Advanced Meson Science Laboratory was launched in 2002 based on a proposal to pursue hadron physics research using the meson as a probe into nuclei to study the strong interaction. At the same time, we are requested to commit to the operation of the RIKEN-RAL branch and promotion of muon science research. The branch is in the Rutherford Appleton Laboratory (RAL) and operated under the UK-Japan scientific agreement on muon science. Thus, our Laboratory is composed of two subgroups to conduct hadron physics research using mesons and to conduct muon science studies covering fundamental particle and nuclear physics to condensed matters physics. Because the research activity in muon science is separately summarized by P. King *et al.* in this volume, let us describe hadron physics research in this article.

By embedding mesons into nuclei and studying the property change of those particles in nuclear media, one can study the physics at densities beyond standard nuclear density, e.g., in neutron star matter, as well as the origin of matter (hadron) mass, in which the standard scenario is that the hadron masses are generated by the spontaneous chiral symmetry breaking of the vacuum. For these studies, we have been conducting experiments at the world's leading accelerator facilities such as Japan Proton Accelerator Research Complex (J-PARC) for K-mesons having s-quarks, and RI Beam Factory (RIBF) for π-mesons consisting of the lightest u- and d-quarks together with their anti-quarks.

Deeply bound pionic atoms are quite interesting systems, in which the π is captured by the nucleus owing to Coulomb interaction and its wave function overlaps with that of the nucleus at the surface. Before our breakthrough experiment at GSI,[1,2] it was believed that the pionic atom cannot be realized if there exist substantial wave-function overlaps between the pion and nucleus. This misunderstanding was strengthened by the fact that the pionic-atom formation by the pion atomic capture at rest is limited up to medium-heavy nuclei, since no observation was realized in heavy nuclei previously.

In our GSI experiment, direct pion formation inside nuclei by feeding it into the atomic state was realized for the first time by introducing the (d, ^{3}He) reaction to lead target at the recoilless condition. In this neutron pickup reaction, $d +$ "n" $\to \pi^- + {}^3$He, the pion can be produced almost at rest for a specific deuteron momentum (momentum transfer to the pion $q_\pi \sim 0$); therefore, it is likely to be captured, and the efficient atomic-state formation is realized.

At RIBF, we extended our research to conduct high-precision isotope-dependence studies on several Sn isotopes to acquire more quantitative information on the atomic shifts systematically. To achieve high precision, we introduced dispersion-matching optics to the BigRIPS spectrometer for the first time by taking advantage of the high-intensity beam available at RIBF. We succeed in demonstrating the outstanding performance of the dispersion-matching optics at the BigRIPS spectrometer. In fact, in the on-line monitor level, the formation of ground state of the pionic atom, together with its several exited states, has already been identified clearly.

To our surprise, a theoretically unexpected excited-state formation was also identified clearly, with the formation yield exhibiting an angular dependence. This angular dependence helps us to identify the quantum number of those excited states without ambiguity. Our analysis shows that the deduced isospin dependence of the energy shifts of the pionic-atom ground states is consistent with the standard scenario of the hadron mass-generation mechanism. We are working on publishing this result.

In the case of the π-meson, the available density range to be studied is limited to the nuclear surface density, which is well below the normal nuclear-matter density. This is because of the repulsive nature of the πN strong interaction. Pion wave functions are pushed away from nuclei, and form a hybrid state in between the atomic and nuclear bound state. Thus, it is quite interesting to know if it is possible to form a pure nuclear meson bound state deep inside nuclei.

In this context, a very interesting meson is the $\eta'(958)$-meson. It is known that its mass is very difficult to explain in a simple quark picture, and the mass deviation of this specific meson is explained by the $U_A(1)$-anomaly. We have just started a new series of experiments to study a bound system of an η' in a nucleus. The first experiment was conducted in GSI by measuring excitation spectra of carbon nuclei in ^{12}C(p, d) reactions near the η'-emission threshold. We achieved a very good resolution of ∼2.5 MeV (σ) and a good statistical sensitivity at a level better than 1%. The measured excitation spectra agree well with theoretical predictions but do not show distinct structures

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due to formation of the η'-nucleus bound systems. The result is interpreted in terms of an interaction between an η' and a nucleus, setting stringent constraints in the optical potential for the first time.[3)] Based on the results, a second experiment is being prepared in FAIR at GSI.

Another very interesting meson is the anti-kaon ($\overline{K}$) in the second-lightest K-meson group having the *strange* (s)-quark as a constituent quark, namely K^- and $\overline{K}^0$. The $\overline{K}N$ interaction was rather poorly known, in contrast to the πN interaction. The interaction seems to be strongly attractive based on the scattering data; therefore, it can form a nuclear bound state, which requires the ground state of the kaonic hydrogen atom to have a strong upward shift due to the pole below the $\overline{K}\,N$ threshold. On the other hand, previous kaonic hydrogen atom data seem to be attractive only very weakly, which is entirely inconsistent with scattering data. We played a very important role again to solve this puzzling situation.

At KEK, we conducted an x-ray measurement of the kaonic hydrogen atom to solve the $\overline{K}N$ interaction puzzle. We utilized a gaseous hydrogen target for the first time to avoid the Stark effect occurring in high-density targets, which reduces the x-ray yield substantially. To compensate for the small number of available kaons at rest in the gas, we placed multi-channel x-ray detectors directly exposed to the hydrogen gas located inside the target cell. In the experiment, we also identified two charged pions as decay products of the kaonic hydrogen atom. Using these two charged pions, we selected the fiducial volume for the target and identified background-free events by choosing the final states, in which no γ-ray can be generated because of the severe x-ray background source. Our work on kaonic hydrogen atom spectroscopy resulted in very clear spectra for the first time, and the strongly attractive interaction between a kaon and nucleon in the $I = 0$ channel is confirmed,[4,5)] together with the scattering data.

This confirmation of strong attraction of the $\overline{K}N$ interaction in the $I = 0$ channel opens up another very curious question. The attraction is so strong that it is more natural to form a bound state between a kaon and proton. In fact, there is a *well-known* resonance called $\Lambda(1405)$, the mass of which is located just below the mass threshold of the kaon and proton, $M(K^-p)$; the resonance is assumed to be an exited state of a member of the Λ hyperon, i.e., it is an excited *uds*-quark baryon system. Thus, it is very natural to ask whether $\Lambda(1405)$ can be interpreted as a bound state of a kaon and proton due to the strong interaction, i.e., $\Lambda(1405)$ = "K^-p". If this is true, then the kaon can form a variety of nuclear bound states together with various nuclear systems. The strong $\overline{K}N$ attractive interaction might help form a high-density nuclear object beyond the standard nuclear density spontaneously. It might also help the study of the in-medium property change of mesons in nuclei.

Therefore, a variety of experimental studies have been conducted by a number of experimental groups to identify the simplest kaonic nuclear bound state, "K^-pp." The detection of the kaonic nuclear state formation is difficult from the kaon absorption at rest because the kaon mainly reacts with one of the nucleons in the mesonic channel and produces a hyperon (Λ or Y) as $K^-\,N \to \pi\,\Lambda$, without forming a kaonic nuclear state. It can also be absorbed by two nucleons simultaneously as $K^-\,N\,N \to \Lambda\,N$, and this process produces huge backgrounds. The direct kaon production channel is also attempted via the $p\,p \to K^+ +$ "K^-pp" reaction. However, this channel has large ambiguity due to the presence of $N^*(1410)$ resonance, which can decay strongly to $K^+\Lambda$. Obviously, no K^- (nor $\overline{K}$) is generated in this reaction channel, and the channel is energetically easier to be produced compared to the $K^+\,K^-$-pair production. One can easily be misled by the reaction chain of $p\,p \to N^*(1410)+p \to (K^+\Lambda)+p$ to be a "K^-pp" formation signal, if one believes the $\Lambda\,p$ in the final state (wrong pair) is the decay product of "K^-pp." There are also other experimental studies to search for the kaonic bound state, but those are limited by either null results or insufficient statistics. Therefore, there is no convincing and conclusive experimental evidence of the existence of the kaonic nuclear bound state.

We employed an entirely different approach at J-PARC K1.8BR beam-line in our experiment E15. We bombarded a K^- beam on a ^{3}He target to knockout a neutron from the target nucleus at 1 GeV/c ($\sqrt{s_{KN}} \sim$ 1.8 GeV/c^2), i.e., $K^- +^3$ He $\to K^-\,p_s\,p_s + n$ (p_s denotes spectator proton). The cross section of this reaction is rather high, because of the presence of the Y^* resonance near 1.8 GeV/c^2, which decays strongly to $\overline{K}N$. There are several key advantages in this reaction channel to search for the kaonic bound state. First, the recoil kaon momentum (or momentum transfer), q_K, is as small as $\sim$200 MeV/c ($\sim p_F$) in this reaction; therefore, one can expect very efficient nuclear formation as $K^-\,p_s\,p_s \to$ "K^-pp." Another advantage is that the presence and the commitment of K^- in this channel is secured from the beginning. Still another advantage is that the two- (or multi-) nucleon absorption reaction can be expected to have a small cross section. Finally, we can cover the target region with a cylindrical detector system (CDS) to identify the final state of "K^-pp" with sensitivity to the decay process. We also placed large-volume neutron counter arrays in the forward direction 15 m away from the target system to identify neutrons in the production channel with a high missing-mass resolution of about 10 MeV/c^2.

The pilot run of J-PARC E15 (E15^{1st}) showed quite remarkable results. The semi-inclusive forward neutron spectrum shows a large yield below the mass threshold of $M(K^-pp)$ as a long tail from the quasi-elastic kaon scattering, implying the existence of strong

$\overline{K}N$ attractive interaction.[6] An even more impressive spectrum was obtained in the Λp invariant mass spectrum of the Λpn final state, in which we observed an event concentration near the $M(K^-pp)$ threshold, and the centroid of the event concentration is well within the bound region.[7] Thus, we conducted a new beam time for further study, especially focusing on the Λpn final state (E15^{2nd}).

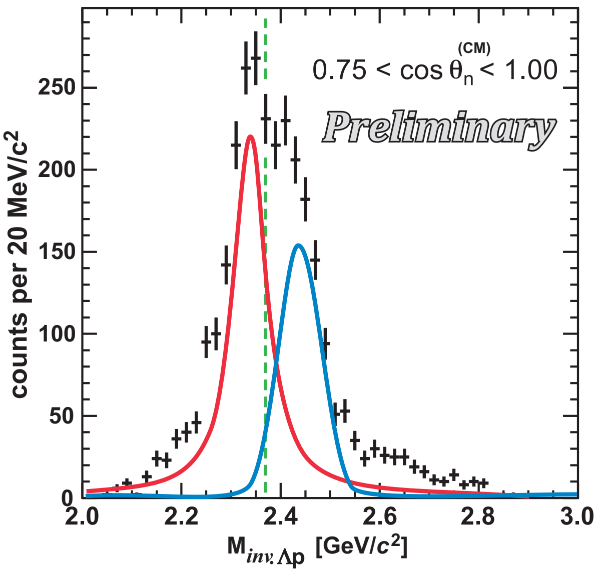

Fig. 1. A preliminary Λp invariant mass spectrum of the Λpn final state of the forward neutron emission ($\cos\theta_n^{\mathrm{CM}} > 0.75$) events, in which a strong event concentration is found. The spectrum is fitted by a Breit-Wigner formula for the bound region (red) and a Gaussian formula for the unbound region (blue), together with a smooth background. The dashed line indicates the mass threshold of $M(K^-pp)$.

We are still in an analysis phase, but the preliminary result is truly astonishing. As shown in Fig. 1, the event concentration near the $M(K^-pp)$ threshold is not a single peak structure, as we simply assumed in our previous publication,[7] but it has clear internal structures separated by the threshold energy indicated by the dashed line. First, the only reasonable explanation of the peak-structure formation below the $M(K^-pp)$ threshold is the kaonic nuclear bound state formation of "K^-pp." Events below the threshold can be generated when virtual kaons below the rest mass are produced in a quasi-elastic (QE) reaction. The peak structure can only be formed when there exists a resonance pole below the threshold, while a smooth tail is formed below the threshold if a pole does not exist. The Λp pair in the final state, together with the forward neutron, ensures that the backscattered K^- interacts with the other two spectator protons. Thus, K^-, $\overline{K}^0$, or $\Lambda(1405)$ escaping channels are naturally suppressed substantially, in contrast to the semi-inclusive missing-mass spectra of ^{3}He$(K^-, n)X$.[6] The peak centroid is located around ∼40 MeV, which is much deeper than that of the normal nuclear system about 10 MeV.

The existence of the structure above the threshold provides further confirmation that the structure below the threshold is actually the nuclear bound state of "K^-pp," in which the constituent particles do not lose their identity in the system. Generally, the peaks in a mass spectrum are isolated in the case of baryonic resonance. In contrast, nuclear-state formations are always associated with the *so-called* quasi-free (QF) processes in the unbound energy region, which indicate that the constituent particles can be dissolved. In this case, the structure above the threshold can be interpreted as the initial kaon backscattered at an energy above the kaon mass in the QE channel, followed by internal conversion (IC) with two spectator protons resulting in Λp in the final state. Thus, this successive reaction can be treated as a QF process of the ^{3}He$(K^-, \Lambda p)n$ reaction channel.

To finalize the present study, we are analyzing the angular distribution of the particles in the final state, to study the form factor, spin, and parity of the observed state, and to prepare an independent analysis of the data so as to reach a confirmative result on the kaonic nuclear bound state "K^-pp." The peak in the bound region would suggest that the ∼ on-shell K^- (or $\overline{K}$) can form a nuclear bound state (Boson & Fermion hybrid system), where u- and $\overline{u}$-quarks coexist, at-least within a time scale allowed by the width of the bound state. It is quite important and interesting to know how the hadron identity is conserved even in nuclear media.

In the future, we wish to study π, η', and K-meson bound states more precisely and to extend our study to nuclear bound states of other mesons, such as η and ϕ, for a global understanding of the hadron mass generation mechanism and the quark-confinement mechanism. We believe that the mesonic nuclear state study is a door to access the mystery of the origin of matter mass in the universe and a laboratory-based showcase to understand the physics of very-high-density matter, such as the core of a neutron star.

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