Strangeness in Nuclear Physics

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Abstract. Strangeness degrees of freedom are not so evident in traditional low-energy nuclear physics. Some effects of strange (s) quarks as sea-quark components, s̅s̅, in a nucleon have been investigated in several measurements. However, their effects are found to be not so large. Strangeness is, somehow, hidden in nature. Nevertheless, it plays an important role when we discuss the QCD phase transitions at high temperature and/or high density. This is because the strange quark mass is close to the typical energy scale of QCD.

The strangeness can be explicitly implanted into a nucleus as the bound states of strange hadrons. By extending our scope of hadron many-body systems into flavor SU(3), the role of strangeness in high density nuclear matter can be investigated.

In this paper, I review the recent topics in the field of strangeness nuclear physics and discuss future prospects in a new facility J-PARC.

1. Strangeness in nucleons and nuclear matter at extreme conditions

A nucleon has three valence quarks with two flavors of up(u) and down(d). Thereby, a nucleus composed of nucleons is made of quarks with two flavors in the first approximation. However, the nucleon is a much more dynamical object in which quantum-chromo dynamics (QCD) controls the dynamics of quarks and gluons within the nucleon. We know there are a lot of quark-antiquark (q̅q) pairs in the nucleon, which include strange quark-antiquark (s̅s̅) pairs as well as uu and dd. Possible effects of the s̅s̅ pairs on the static properties of nucleons have been investigated both theoretically and experimentally.

One example is a series of experimental efforts at MIT-Bates [1], Mainz [2], and Jefferson Laboratory(JLab) [3, 4] to use parity violating electron scattering to extract the strange vector form factors. Using these data, a careful global analysis determined the strange form factors at a four-momentum transfer of \(Q^2 = 0.1 \ (GeV/c)^2\) [5]; The strange charge(magnetic) form factor \(G_E^s(G_M^s)\) is estimated to be -0.008 ± 0.016(0.29 ± 0.21). Recently, the PVA4 collaboration has reported the strange form factors at the four momentum transfer of \(Q^2 = 0.22 \ (GeV/c)^2\) to be \(G_E^s = 0.050 \pm 0.038 \pm 0.019\) and \(G_M^s = -0.14 \pm 0.11 \pm 0.11\) [6]. New data from the G0 collaboration also indicates a strange quark contribution of \(\leq 10\%\) of the electric and magnetic form factors at \(Q^2 = 0.22\) and 0.63 \((GeV/c)^2\) [7]. Rapid progresses in lattice QCD calculations enable us to obtain the nucleon strangeness form factors to good precision. A recent calculation shows \(G_E^s = 0.0022 \pm 0.0019\) and \(G_M^s = -0.015 \pm 0.023\) at \(Q^2 = 0.1 \ (GeV/c)^2\) [8]. All of these analyses indicate that the strange quark contributions to the nucleon form factors are "small". The strange quark contribution to the nucleon mass has been calculated with lattice QCD, too. Earlier estimates using chiral perturbation theory suggested a large strange quark content. However, recent lattice calculations suggest the strange quark content is less than 5%...
of the nucleon mass [9]. Thus, the strange quark-antiquark pairs in the nucleon do not explicitly contribute to the properties of nucleon.

On the other hand, the strangeness degrees of freedom play a significant role in the discussions of QCD phase transitions of nuclear matter at high temperature and/or high density. This is because the strange quark mass (92.5±2.5 MeV/c^2) is close to the typical energy scale of QCD. \( \Lambda_{QCD} \approx 150-250 \) MeV. In the QCD phase transition at a high temperature of \( \approx 170 \) MeV, the lattice QCD simulations suggest that the phase transition from hadronic gas to quark-gluon plasma is a second-order phase transition with two \((u, d)\) flavors, but it is just a crossover with three \((u, d, \text{and } s)\) flavors. In the high-density regime, the lattice QCD technique is not applicable due to the phase problem at finite chemical potential. Nevertheless, various theoretical models are proposed with respect to QCD. While a two-flavor color superconducting phase is suggested to exist with the first order phase transition at high density, a color-flavor locked phase [10] is expected to appear with three flavors in the higher density region. Such high-density matter is expected to be realized within neutron stars because of the large gravitational energy. It is essential to investigate the role of strangeness in high-density matter to understand the inner structure of the neutron star.

2. Recent Topics and Prospects in Strangeness Nuclear Physics

Strangeness \((S)\) can be directly implanted into a nucleus as the bound states of strange hadrons, such as hyperons \((\Lambda, \Sigma, \text{and } \Xi)\) and \(K\) mesons, with a nucleus in strong interaction. Such experimental investigations are, at present, conducted in various accelerator facilities around the world. In the US, a series of hypernuclear experiments have been carried out both in Hall A and Hall C of JLab using \((e, e'K^+)\) reactions since 2000 [11, 12]. High resolution magnetic spectrometers were constructed for \(\Lambda\) hypernuclear spectroscopy with a good energy resolution of 0.3–0.7 MeV (FWHM) [13, 14]. A big surprise is the report of anti-hyper-triton production at the Relativistic Heavy Ion Collider (RHIC) by the STAR collaboration [15]. It demonstrated the usefulness of the high-energy heavy ion collisions to produce such exotic nuclei. In Europe, the DAΦNE \(\phi\) factory in Italy has been used for the \((K_{\text{stop}}, \pi^+)\) reactions to produce \(\Lambda\) hypernuclei, Kaonic atoms and Kaonic nuclei since 2003. At GSI, a new experimental program to produce light hyperfragments with heavy-ion beams has recently started [16]. In Germany, there is also an experimental program at Mainz [17] to utilize the \((e, e'K^+)\) reaction to produce \(\Lambda\) hypernuclei. In Japan, after a lot of successes in strangeness nuclear physics at the High Energy Accelerator Research Organization (KEK), a new high-intensity proton accelerator complex, J-PARC, has started beam commissioning since 2009. Here I describe an overview of the recent results obtained in these facilities and several examples of the proposed experiments at J-PARC.

2.1. \(S=-1\) Baryon Systems

2.1.1. Production of \(\Lambda\) hypernuclei via \((\pi^\pm, K^+)\) reactions

For the first time, it was demonstrated at Brookhaven National Laboratory (BNL) [18] that the \((\pi^+, K^+)\) reaction was effective to produce the \(\Lambda\) single-particle orbitals. Then, the production of \(\Lambda\) hypernuclei in a wide mass-number range of \(\Lambda_{\text{Li}}, \Lambda_{\text{Be}}, \Lambda_{^{10}\text{B}}, \Lambda_{^{12}\text{C}}, \Lambda_{^{13}\text{C}}, \Lambda_{^{16}\text{O}}, \Lambda_{^{28}\text{Si}}, \Lambda_{^{31}\text{V}}, \Lambda_{^{80}\text{Y}}, \Lambda_{^{130}\text{La}}\) and \(\Lambda_{^{208}\text{Pb}}\) has been successfully carried out [19, 20, 21] at the 12-GeV proton synchrotron (PS) of KEK by using the SKS spectrometer [22]. The spectrometer has a good momentum resolution of \(\Delta p/p = 1/1000\) at 720 MeV/c and a large acceptance of 100 msr. Owing to the good energy resolution of 2.0–2.3 MeV (FWHM), the \(\Lambda\) single-particle orbits were clearly identified up to heavy \(\Lambda\) hypernuclei. The high momentum transfer of \(\approx 350\) MeV/c of the \((\pi^+, K^+)\) reaction selectively populated the spin-stretched states. This made the excitation spectra rather simple. In Fig. 1, the hypernuclear mass spectra of \(\Lambda_{^{80}\text{Y}}\) are shown as an example [20].

One good feature of the \((\pi^\pm, K^+)\) reactions is a very low experimental background. There is no decay-in-flight background from the incident pion beam. Therefore, such a trial to look
for neutron-rich Λ hypernuclei with the double charge-exchange (π−, K+) reaction has been carried out in KEK-PS E521, although the production cross section could be very small. In the 10B(π−, K+) reaction at 1.2 GeV/c, the production cross section of 11.3±1.9 nb/sr was obtained for 10ΛLi [23], which demonstrated the (π−, K+) reaction was promising to produce neutron-rich hypernuclei for the first time. At J-PARC, an experiment, J-PARC E10, is planned to measure the 6Li(π−, K+) reaction to produce 6ΛH by utilizing a high-intensity π− beam.

2.1.2. Hypernuclear Gamma-ray Spectroscopy One of the major highlights in Λ hypernuclear spectroscopy is the success of hypernuclear γ-ray spectroscopy with the Hyperball detector [24]. It greatly improved the energy resolution of hypernuclear spectroscopy from a few MeV to a few keV. The Hyperball detector consisted of fourteen sets of coaxial N-type Ge detectors equipped with fast electronics and BGO counters around each Ge crystal. The photo-peak efficiency for all the Ge detectors is 2.5% at 1 MeV. In the experiment KEK E419, the lifetime of the 5/2+ state in 7ΛLi was measured by observing the E2(5/2+ → 1/2+) transition at 2050 keV with the Doppler shift attenuation method [25]. The high resolution of the Hyperball detector was the key to carry out such a shape analysis. By comparing with that for the 6Li core, a significant shrinkage of the core by about 19% was concluded. This is the first demonstration of the "glue-like role" of the Λ. The M1 transition (3/2+ → 1/2+) was also observed at 692 keV for the first time, whose energy strongly depends on the ΛN spin-spin interaction.

The Hyperball detector was transported to BNL after the first successful run in E419. There, they continued the measurements in p-shell hypernuclei via the (K−, π−) reactions. It was brought back to KEK in early 2002, and used for several more experiments. In these measurements, the important level splittings (see Fig. 2) were resolved with the Hyperball, and information on the spin-dependent ΛN interactions has been extracted; such as the spin-spin,
symmetric and anti-symmetric spin-orbit, and tensor terms [26].

A new germanium detector Hyperball-J is now under construction for the J-PARC E13 experiment. It consists of about thirty sets of Ge detectors having a photo-peak efficiency of about 75% relative to the 3"×3" NaI detector. Each Ge detector is surrounded with fast PWO counters for background suppression. The photo-peak efficiency is expected to be better than 5% at 1 MeV at the distance of ~15 cm from the target.

One of the important subjects is to measure the transition probabilities ($B(M1)$) of the Λ spin-flip $M1$ transitions, with the aim of probing the $g$–factor of a Λ hyperon within a nucleus. A measurement of the $M1(3/2^+ → 1/2^+)$ transition of $\Lambda^7\text{Li}$ seems to be promising. Considering the estimated lifetime of the $3/2^+$ state of ~0.5 ps, a Li$_2$O target with a density of 2.01 g/cm$^3$ in granular powder has been selected to apply the Doppler shift attenuation method.

2.1.3. Production of Σ hypernuclei In 1980's, there were a lot of experimental reports which claimed narrow peak structures of the widths less than 10 MeV in the quasifree region of Σ productions [27]. Later, these observations were experimentally denied with much better statistics data taken at BNL [28]. On the other hand, the existence of a $\Sigma^+\text{He}$ bound state, which was first claimed in the $^4\text{He}(K_{\text{stop}}^-,\pi^-)$ reaction [29], was clearly confirmed in the in-flight $^4\text{He}(K^-,\pi^-)$ reaction at 600 MeV/$c$ at BNL [30]. Up to now, there have been no other measurements claiming other bound states of the Σ hyperon. On the other hand, it is believed that the $\Sigma^-$–nucleus potential would be strongly repulsive in medium to heavy nuclear systems based on the measurement of the $(\pi^-,K^+)$ spectra at 1.2 GeV/$c$ near the $\Sigma^-$ production threshold in KEK-PS E438 [31].

2.2. $S=-2$ Baryon Systems

The $(K^-,K^+)$ reaction at the $K^-$ incident momentum of around 1.8 GeV/$c$ has been used for the production of $S=-2$ systems: double Λ hypernuclei and Ξ hypernuclei. A Ξ$^-$ hyperon is produced through the $K^- + p → K^+ + \Xi^-$ reaction.

Figure 2. Summary of recently observed gamm-ray transitions by H. Tamura [24].
2.2.1. Double-Λ hypernuclei  Before two hybrid-emulsion experiments at KEK-PS, E176 and E373, there were two old emulsion events [32] of double-Λ hyperfragments. While the identification and interpretation of these old events had been criticized at that time, a new event observed in KEK E176 established the existence of double-Λ hypernuclei [33]. However, they were not able to uniquely identify the hypernuclear species nor the binding energy.

In KEK E373 they succeeded to uniquely identify the formation of $^6_{\Lambda\Lambda}$He and measure its binding energy [34]. The event was named the "Nagara Event" (Fig. 3). The Λ-Λ bonding energy ($\Delta B_{\Lambda\Lambda}$) was extracted to be $1.01\pm0.20^{+0.18}_{-0.11}$ MeV, for the first time, which has been updated to $0.67\pm0.17$ MeV [35] because of an update of the Ξ− mass. This value of $\Delta B_{\Lambda\Lambda}$ is smaller than the previously believed value of about 4.7 MeV. In KEK E373, there exist three other candidates of double-Λ hyperfragments [35]. Unfortunately, the accuracy of event identification for those is not as good as that in the "Nagara Event".

It is proposed to enhance the number of stopped Ξ− by a factor of 10 compared with E373 in a new measurement, E07, at J-PARC [35]. More double-Λ events with clean identification are expected and will be used to investigate the systematics of binding energies of light double-Λ hypernuclei.

2.2.2. Ξ hypernuclei  There is almost no experimental information on the ΞN interaction. Only limited information is available for elementary processes, $\Xi N \rightarrow \Xi N$ and $\Xi^- p \rightarrow \Lambda \Lambda$ [36, 37]. Nevertheless, there exist several theoretical models extending the nucleon-nucleon force for hyperon-nucleon/hyperon-hyperon interactions [38, 39, 40]. Recently, there is also an attempt to calculate the $\Xi N$ potential based on a lattice QCD technique [41]. At this moment, it is still ambiguous if $\Xi$ hypernuclei exist or not as a bound state. Even if the potential depth is deep enough to form a few bound states, there is a possibility that the bound state peaks could not be resolved because of a large conversion width due to $\Xi^- p \rightarrow \Lambda \Lambda$. Isospin dependence of the Ξ-nucleus potential is another important issue to be explored. Spin-dependent $\Xi N$ interactions are also unknown. In a naive quark model, the spin-orbit $\Xi N$ interaction is expected to be as large as that in the nucleon case. As for heavy Ξ hypernuclear productions, there is an idea that the Coulomb-assisted bound states might be observed rather cleanly [42].
$\Xi$ hypernuclei can be directly produced via the $(K^-, K^+)$ reaction. Such measurements were carried out at KEK [43] and BNL [44] for the $^{12}_{\Lambda}\Xi$ Be reaction. However, the energy resolution of the spectrometers and statistics were not enough to observe the bound-state peaks of $\Xi$ hypernuclei. From the yield in the bound region, BNL E885 reported that the cross section for the $^{12}_{\Lambda}\Xi$ Be reaction at 1.8 GeV/c was $89\pm14$ nb/sr for the angular average from $0^\circ$ to $8^\circ$. Assuming the Woods-Saxon type potential, a potential depth was obtained to be -14 MeV for $A=12$ from a spectrum shape analysis near the binding threshold.

The J-PARC E05 experiment aims to observe a bound-state peak in the $^{12}_{\Lambda}\Xi$ Be reaction with the energy resolution of 2.5 MeV (FWHM). A new $K^-$ beam line, K1.8, has been constructed in the Hadron Experimental Hall of J-PARC. The beam line has a double-stage electro-static mass separator system to achieve a good $K^-/\pi^-$ ratio greater than 5 and a beam line spectrometer section at the end of the beam line to have a good momentum resolution ($\Delta p/p=1.4\times10^{-4}$ in rms). For the scattered $K^+$ measurement, the SKS spectrometer has been moved from KEK Tsukuba to J-PARC. A small dipole magnet will be installed in front of the SKS to give a larger bending power for the $(K^-, K^+)$ reaction at 1.8 GeV/c. Once the existence of $\Xi$ hypernuclei is established for $^{12}_{\Lambda}\Xi$ Be, it is important to observe several light $\Xi$ hypernuclei to investigate the spin and isospin dependence of the $\Xi$-nucleus potential.

Double $\Lambda$ hypernuclei could be, in principle, populated in the $(K^-, K^+)$ reaction. There are two reaction mechanisms. The first one is a two-step mechanism; $K^- p \rightarrow \pi^0 \Lambda, \pi^0 p \rightarrow K^+ \Lambda$. It is estimated to have a very small production cross section of $\leq 1$ nb/sr in the forward direction. The other one is a direct production process through virtual $\Xi$ states with the mixing of $\Xi^- p \rightarrow \Lambda\Lambda$. Since the energy difference between the $\Xi N$ states and $\Lambda\Lambda$ states is small, this mechanism could give us a larger production cross section of $\geq 10$ nb/sr depending on the coupling strength of $\Xi N-\Lambda\Lambda$ [45]. In this regard, it is important to measure the width of the $^{12}_{\Lambda}\Xi$ Be bound state in J-PARC E05.

2.3. Kaonic Nuclei
In elementary $KN$ interactions, there was a conflict between low-energy $KN$ scattering analyses and energy shifts observed in Kaonic hydrogen X-rays. This puzzle was solved with a clean measurement of the Kaonic hydrogen X-ray [46]. It turned out that there is a strong attraction in the $KN$ interaction in the isospin $(I)=0$ channel. A possibility to have deeply-bound kaonic
nuclei due to this strong attraction was suggested by several authors. Among them, Akaishi and Yamazaki [47] predicted the possible presence of discrete nuclear bound states of $\bar{K}$ in few-body nuclear systems. The binding energies and widths of few-body systems involving a $\bar{K}$ were calculated from $\bar{K}N$ interactions which were constructed so as to account for the $\bar{K}N$ scattering lengths, the $K^{-}p$ atomic shift and the energy and width of $\Lambda(1405)$ under the assertion that $\Lambda(1405)$ is a bound state of $\bar{K}N$. It became clear that the strong attraction of the $I = 0$ $\bar{K}N$ interaction plays an important role in accommodating deeply bound states in proton-rich systems. Very deep and narrow bound states, $3\bar{K}H(I = 0) \equiv K^{-} \otimes ^3\text{He} + K^0 \otimes ^3\text{H}$ ($I = 0$) and $\bar{K}^4\text{He} \equiv K^{-} \otimes ^4\text{He}$, with $K$ binding energies of 108 and 86 MeV and widths of 20 and 34 MeV, respectively, were predicted.

In-flight ($K^{-}, n/p$) reactions at the $K^{-}$ incident momentum of 1 GeV/$c$ were used to produce kaonic nuclei in KEK-PS E548 by Kishimoto’s group [48]. The inclusive spectra of the $^{12}\text{C}(K^{-}, n)$ and $^{12}\text{C}(K^{-}, p)$ reactions were measured. They observed a significant amount of events in the $K^{-}$ bound region. However, the bound states of kaonic nuclei were not identified as clear peaks. From the spectrum shape analysis, the $K^{-}$ potential depths of -190 MeV and -160 MeV were estimated from each spectrum, which suggest the $\bar{K}$ nucleus potential is deep.

In the FINUDA experiment, a different approach was applied to look for kaonic nuclear fragments in the $K^{-}$ absorption reactions at rest. Rather abundant production of $\Lambda-p$ pairs emitted in back to back in the laboratory system were observed in the $K^{-}$ absorption on $^6\text{Li}$, $^7\text{Li}$, and $^{12}\text{C}$ targets. It was a surprise that the invariant mass of the $\Lambda p$ pair was significantly smaller than the mass of the $K^{-}pp$ system [49]. It was claimed that a kaonic bound state of $K^{-}pp$ was formed in the stopped $K^{-}$ absorption in the surface region of nuclei and decayed into the $\Lambda p$ pair. The binding energy of $115^{+6}_{-5}(\text{stat})^{+3}_{-2}(\text{syst})$ MeV and the width of $67^{+14}_{-11}(\text{stat})^{+2}_{-3}(\text{syst})$ MeV were obtained. However, the reaction mechanism to produce such a deeply-bound $K^{-}pp$ system in the stopped $K^{-}$ absorption is not known well. Therefore, as for the interpretation of this mass shift, other interpretations [50] could not be excluded.

Since the $K^{-}pp$ system must be the simplest nuclear $\bar{K}$ bound state, if it exists, a lot of work to theoretically examine the existence of the $K^{-}pp$ system has been carried out by using reliable few-body techniques. Faddeev calculations have been carried out by Shevchenko et al. [51] and by Ikeda and Sato [52]. Yamazaki and Akaishi [53, 54], and Doté et al. [55] have done calculations based on variational approaches. All of these calculations have confirmed that
the $K^-pp$ bound state must exist with the binding energy of 20 to 70 MeV depending on the $\bar{K}N$ interaction models used in the calculations. However, it depends on the width of the bound state whether the state is experimentally observed as a peak structure or not. The width can be as large as $\sim 100$ MeV when the binding energy is small.

After the FINUDA observation, there have been several reports on possible signals of the $K^-pp$ in heavy ion collisions by the FOPI group [56], in antiproton-$^4\text{He}$ annihilation by the OBELIX group [57], and in proton-proton collision by the DISTO group [58]. However, the obtained binding energies etc. are not conclusive.

Therefore, it is of vital importance to experimentally confirm the existence of the $K^-pp$ bound state. Already at J-PARC, experiment E15 to search for the $K^-pp$ in the $^3\text{He}(K^-,n)$ reaction at 1 GeV/$c$ is approved as one of the Day-1 experiments at the Hadron Experimental Hall. There is also a new experiment E27 to look for it in the $d(\pi^+,K^+)$ reaction at 1.5 GeV/$c$.

3. Summary

Strangeness is a key to understand the dynamics of high-density QCD. New $K^-$ beam lines at J-PARC are now in operation and give us good opportunities to investigate the role of strangeness in nuclear matter; in particular, at high density. Construction of the new detector systems to perform the $\Xi$ hypernuclear spectroscopy, hypernuclear $\gamma$-ray spectroscopy, kaonic nuclear search experiments etc. are now in rapid progress.

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