EPJ Web of Conferences **271**, 12001 (2022) https://doi.org/10.1051/epjconf/202227112001
HYP2022

Overview of hypernuclear and strange particle physics

–Experimental summary of HYP2022

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Abstract. Recent results and future prospects in strangeness nuclear and hadron physics are summarized from an experimental point of view based on plenary presentations in the HYP2022 conference.

1 Introduction

The 14th International Conference on Hypernuclear and Strange Particle Physics was held in Prague from June 27 through July 1, 2022, hosted by Nuclear Physics Institute (NPI Řež) of the Czech Academy of Sciences and the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague (FNSPE CTU). The conference covered various aspects in hadron and nuclear physics with strangeness. In this paper, experimental results and prospects in this field are summarized based on the experimental plenary talks given in the conference. It is to be noted that not all the talks are sufficiently covered.

2 Hypertriton and few-body hypernuclear systems

2.1 Significance and status of the hypertriton

One of the main subjects in this field is how to understand and describe the baryon-baryon interactions. The ΛN interaction, the most basic part of this subject, has been studied with various theoretical approaches, but the experimental information is still not satisfactory due to insufficient ΛN scattering data. In this situation, the hypertriton (${}^{3}_{\Lambda}$H), the lightest bound Λ hypernucleus, plays particularly important roles as the deuteron did in the study of NN interactions. However, experimental data for hypertriton are not firmly established.

Although binding energies, level structures and lifetimes of various Λ hypernuclei have been studied via counter experiments with direct reactions such as (K^-, π^-), (π^+, K^+) and $(e, e'K^+)$ since 1970s up to now, but the data for the hypertriton has not been updated due to experimental difficulties from those with large errors determined by the old emulsion experiments in 1960-70s.

"Hypertriton puzzle" arose when the heavy ion collision experiments (HypHI, then ALCIE and STAR) produced hypertritons and reported its lifetime significantly shorter than the free Λ lifetime $\tau_\Lambda = 263$ ps. The reported value of the hypertriton binding energy combined for several emulsion experimental data is quite small ($B_\Lambda = 0.13 \pm 0.05$ MeV), suggesting that

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the Λ wavefunction in ${}^{3}_{\Lambda}$H is widely spread as $[2\mu_{\Lambda d} B_{\Lambda}({}^{3}_{\Lambda}\mathrm{H})]^{-1/2} \sim 15$ fm and consequently the ${}^{3}_{\Lambda}$H lifetime is expected to be almost the same as τ_{Λ}.

During this decade, importance of the lifetime and the binding energy of the hypertriton is recognized and various experimental efforts have been made. Table 1 shows the recent results and the present status of experiments reported in the HYP2022 conference.

2.2 Hypertriton lifetime

In the heavy ion collision experiments, STAR, ALICE and HADES reported new values of the hypertriton lifetime. STAR once reported a quite short lifetime ($142^{+24}_{-21} \pm 29$ ps) [1] in 2018, but a new result (221±15±19) ps from Beam Energy Scan II (BES-II, 3.0 and 7.2 GeV) is significantly different from the previous one and close to the free lifetime [2]. It is noted that since hypernuclear production rates increase for lower energy collision, the Beam Enrergy Scan data contain more light hypernuclear events including ${}^{5}_{\Lambda}$He. ALICE collaboration, which reported a value of $242^{+34}_{-38} \pm 17$ ps [3] in 2019, is updating it to a new value with a smaller error close to the free lifetime [4]. In addition, HADES at GSI reported a preliminary result of 256 ± 22 ± 36 ps [5]. These recent data from heavy ion experiments seem to be converged to a value consistent or slightly lower than the free Λ lifetime.

The hypertriton lifetime puzzle was first raised by HypHI group at GSI with ^{6}Li beam at 2 GeV/A on ^{12}C target [6]. In order to improve the lifetime data for light hypernuclei as well as to confirm the suggested Λnn bound state, the group has organized a new collaboration and just conducted data-taking of the updated experiment employing FRS combined with the WASA detector moved from Juelich [7].

In the heavy ion collision experiments, the lifetime is measured as the flight length of the hypernucleus between the production point and the decay point. In order to obtain reliable lifetime value, a different type of measurement with different systematic errors is necessary. At J-PARC, the experiment E73 is being performed for a direct time measurement between

Table 1. Present status and prospects of ${}^{3}_{\Lambda}$H (and ${}^{4}_{\Lambda}$H) experiments presented in HYP2022. The data reported after the previous HYP2018 are given. $\tau({}^{3}_{\Lambda}\mathrm{H})$ and $\tau({}^{4}_{\Lambda}\mathrm{H})$ are the measured lifetimes of ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H, respectively, in ps, and $B_{\Lambda}({}^{3}_{\Lambda}\mathrm{H})$ is the measured Λ binding energy of ${}^{3}_{\Lambda}$H in MeV.

Experiment	Reaction	Method	$\tau({}^{3}_{\Lambda}\mathrm{H})$	$\tau({}^{4}_{\Lambda}\mathrm{H})$	$B_{\Lambda}({}^{3}_{\Lambda}\mathrm{H})$
STAR [2]	HI (Au+Au)	decay length	$142^{+24}_{-21} \pm 29$		0.41±0.12±0.11
	$\sqrt{s}$ = 3.0, 7.2 GeV		221±15±19	218±6±13	analysis
ALICE [4]	HI (Pb+Pb) $\sqrt{s}$ = 5 TeV	decay length	$242^{+34}_{-38} \pm 17$		(~0.05)
HADES [5]	HI (Ag+Ag) $\sqrt{s}$ =2.55 GeV	decay length	256±22±36	222±8±13	
WASA-FRS [7]	HI (^{6}Li+^{12}C)	decay length	analyzed	analyzed	analyzed
J-PARC E73 [8]	^{3}He(K^{-},π^{0})	decay time	run soon	(190±8±?)	-
MAMI [11]	^{7}Li(e, K^{+})	decay π momentum	-	-	running
J-PARC E07 [7]	K^{-}+emulsion	decay time/energy	analyzed	to be analyzed	analyzed
JLab E12-19-002 [12]	^{3}He$(e, e'K^{+})$	missing mass	-	-	approved

production and decay. The hypertriton is produced by ^{3}He(K^-, π^0) reaction in which energetic photons from π^0 are tagged and the monochromatic pion from ${}^{3}_{\Lambda}$H $\to$ ^{3}He π^- is detected and used to measure the decay time. The group confirmed this method by measuring the ${}^{4}_{\Lambda}$H lifetime via the ^{4}He($K^-.\pi^0$) reaction and ${}^{4}_{\Lambda}$H $\to$ ^{4}He π^- decay, and by identifying the ${}^{3}_{\Lambda}$H decay from ${}^{3}_{\Lambda}$H $\to$ ^{3}He π^- [8]. The ${}^{3}_{\Lambda}$H lifetime measurement will be conducted in 2023.

2.3 Hypertriton binding energy

The experimental value of the hypertriton binding energy, $B_\Lambda({}^{3}_{\Lambda}\mathrm{H}) = 0.13 \pm 0.05$ MeV, is given as the average of rather diverged three values of old emulsion experiments, and it was not updated for a long time. Recently, STAR reported a significantly larger value of $B_\Lambda({}^{3}_{\Lambda}\mathrm{H}) = 0.41 \pm 0.12 \pm 0.11$ MeV [9], suggesting that the lifetime can be significantly shorter than the free Λ lifetime. On the other hand, ALICE reported a preliminary value of less than 0.1 MeV in the conference [4]. STAR BES-II data is also being analyzed [10].

In such invariant mass measurement in high energy experiments, however, it seems difficult to reduce the systematic error down to a few 10 keV. Two different types of approaches have also been pursued. At MAMI the $B_\Lambda({}^{3}_{\Lambda}\mathrm{H})$ value is going to be precisely determined with a precision of ±20 keV via a momentum measurement of the weak decay pion in ${}^{3}_{\Lambda}$H$\to$^{3}He+π^- [11]. In order to calibrate the pion magnetic spectrometer using MAMI's electron beams, a novel method to precisely determine the beam energy using interference of the undulator light has been developed.

Another type of measurement is being carried out with K^--irradiated emulsion in the J-PARC E07 experiment. A machine learning method has been introduced in the emulsion analysis to search for hypertriton decay images [7]. They have found several hypertriton events and aim at obtaining the binding energy with a statistical error of 30 keV and a systematic error of 30 keV.

These various efforts in the lifetime and binding energy measurements will allow us to solve the hypertriton puzzle and precisely and reliably determine these basic quantities for the *YN* interactions.

2.4 Λnn and $\Lambda NN(T = 1)$ systems

The HypHI group reported possible existence of a weakly-decaying Λnn bound state from a ^{6}Li + ^{12}C experiment, although theoretical studies disfavor the existence of the bound state. An experiment with the same reaction was just performed by the WASA-FRS collaboration and the data analysis is in progress [7]. On the other hand, the ^{3}H($e, e'K^+$) reaction was also studied at JLab Hall A with a tritium target in order to clarify the situation. The missing mass spectrum did not exhibit a significant peak around the Λ-binding threshold and an upper limit of the Λnn production cross section was obtained [13]. Theoretically, possible existence of a Λnn resonance state is suggested, and the measured spectrum seems to exhibit a hint of an enhancement just above the threshold. Thus, the experiment had better be repeated with better statistics in the near future.

If the Λnn state is bound, the ${}^{3}_{\Lambda}$H(T=1) state belonging to the same T=1 isotriplet can be investigated via γ-ray spectroscopy because the ${}^{3}_{\Lambda}$H(T=1) $\to$ d + Λ decay is suppressed by isospin conservation. In addition, the ${}^{3}_{\Lambda}$H(T=0) ($3/2^+ \to 1/2^+$) γ transition may be also observed if the $B_\Lambda({}^{3}_{\Lambda}\mathrm{H})$ value is large enough to make the ${}^{3}_{\Lambda}$H(T=0) ($3/2^+$) state bound. It would provide valuable information on the ΛN-ΣN interaction, which may significantly affect the ΛN spin-spin interaction in nuclear matter. A γ-ray spectroscopy experiment for ${}^{4}_{\Lambda}$H and ${}^{3}_{\Lambda}$H is planned as J-PARC E63 [14] with the main motivation of precisely measuring the ${}^{4}_{\Lambda}$H ($1^+ \to 0^+$) γ ray for studying the charge symmetry breaking in A=4 hypernuclei. Here, ${}^{4}_{\Lambda}$H and ${}^{3}_{\Lambda}$H are simultaneously produced as hyperfragments from the ^{7}Li(K^-, π^-) reaction.

3 $S = -2$ systems

The double strangeness systems have been intensively studied at J-PARC. Three types of experiments, emulsion experiments, Ξ hypernuclear missing-mass spectroscopy, and Ξ atomic X-ray measurement, are being carried out and valuable results are coming.

3.1 $S = -2$ nuclei with emulsion

In the J-PARC E07 experiment, Ξ^- hyperons produced by the (K^-,K^+) reaction were injected into emulsion stacks and their images were analyzed with an automatic microscope scanning system with a help of the information on the measured Ξ^- injection point to the emulsion [15]. At present, 33 events of double strange hypernuclei have been observed, and among them, two events of ${}^{15}_{\Xi}$C hypernucleus decaying to twin hypernuclei (IBUKI and IRRAWADDY events) were identified. The IBUKI event gives, for the first time, an accurate value of the Ξ binding energy as $B_\Xi = 1.27 \pm 0.21$ MeV, which is in agreement with one of the two candidate values derived from the KISO event. On the other hand, the IRRAWADDY event gives a much larger value of $B_\Xi = 6.27 \pm 0.27$ MeV. Together with the reanalyzed value of the KINKA event from KEK E373 (8.00 ± 0.77 or 4.96 ± 0.77 MeV) , it was concluded that IRRAWADDY and KINKA correspond to the nuclear s_Ξ-state and IBUKI and KISO to the p_Ξ-state. This result shows a Ξ-nuclear potential with a certain depth and a quite small imaginary part. In addition, a new $\Lambda\Lambda$ hypernucleus (${}^{11}_{\Lambda\Lambda}$Be, MINO event) was observed and the Λ-Λ interaction energy was obtained as $\Delta B_{\Lambda\Lambda} = 1.87 \pm 0.37$ MeV, which should be consistently explained with the value from the NAGARA event, $\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV for ${}^{6}_{\Lambda\Lambda}$He.

3.2 Ξ hypernuclear missing-mass spectroscopy

Since the emulsion method cannot observe exited states of hypernuclei, the missing mass spectroscopy of the (K^-, K^+) reaction is also important. Following a pilot run (J-PARC E05), an upgraded experiment for ^{12}C$(K^-, K^+){}^{12}_{\Xi}$Be reaction (J-PARC E70) with a new dedicated magnetic spectrometer (S-2S) is under preparation [16]. Employing an active target with plastic scintillator, a ${}^{12}_{\Xi}$Be spectrum will be measured with a resolution of 2 MeV(FWHM). Then, ${}^{7}_{\Xi}$H will be also studied via ^{7}Li(K^-, K^+) reaction (J-PARC E75).

3.3 Ξ-atomic X rays

Measurement of Ξ^--atomic X rays provides another means to investigate Ξ-nucleus interaction. At J-PARC, two types of experiments were carried out [17]. In the E07 experiment described above, nuclear absorption of Ξ^- in emulsion atoms was identified via image analysis of emulsion. In the E03 experiment dedicated to Ξ-atomic X rays, Ξ^- hyperons produced by the (K^-, K^+) reaction were stopped in an iron target. In both experiments, Ξ-atomic X rays are measured with a germanium detector array. Data analysis is in progress.

4 YN, YY interactions

Because of experimental difficulties in YN scattering experiments, hypernuclear data have been used to supplement our understanding of YN interactions. Employing plenty of Λ hypernuclear data, the ΛN interaction has been well restricted and the properties of various Λ hypernuclei are able to be understood. However, this approach cannot be extrapolated to high density baryonic matter in neutron stars. In order to extract information on the nuclear density dependence of the ΛN interaction in matter (in the other words, the ΛNN interaction) from Λ hypernuclear data and to properly describe high density matter in neutron stars, two-body YN interaction data in the free space is indispensable. In the case of ΣN interaction, hypernuclear data cannot be used because they are not available except for ${}^{4}_{\Sigma}$He due to repulsive nature of ΣN interaction, .

Recently, two experimental breakthroughs have been achieved. One is a new type of high statistics YN scattering experiments, and the other is so-called "femtoscopy", baryon-baryon momentum correlation measurement in high energy nuclear collision experiments.

4.1 YN scattering

Because of a short flight length of hyperons, previous YN scattering experiments employed visual detectors such as bubble chambers and scintillating fibers with image intensifier tubes. Such "slow methods" strongly restricted event rates and data acquisition rates. Recently, those difficulties have been solved by employing fast detectors and a fast data acquisition system.

The J-PARC E40 group successfully carried out a high-statistics $\Sigma^{\pm}$-p scattering experiment [18]. By employing a fast tracking detector made of scintillating fibers individually read out by SiPM sensors, they measured differential cross sections of Σ^{+}-p and Σ^{-}-p elastic scattering and $\Sigma^{-}p \rightarrow \Lambda n$ reaction at $p_{\Sigma} = 0.45 - 0.8$GeV/c. In the $\Sigma^{+}p$ channel, the obtained cross section was converted to the phase shift, showing that the $\Sigma^{+}p$ interaction has a much stronger repulsive core than the NN interaction, which is interpreted as a result of Pauli principle in the quark level.

At JLab, the CLAS collaboration derived high-statistics Λp total cross sections for $p_{\Lambda} = 0.9 - 2.0$ GeV/c, the momentum region relevant to the core of neutron stars, by using Λ hyperons which are photo-produced in a hydrogen target and scattered there [19].

4.2 Femtoscopy for YN and YY interactions

Momentum correlation of two hadrons emitted in high-energy nuclear collisions provides a unique and powerful means to investigate the strong interaction between the two hadrons. The correlation function $C(k^{*})$, the distribution of the relative momentum k^{*} for two particles in the same event divided by the one for two particles in different events, is described in terms of the source function $S(r^{*})$ and the wave function of the relative coordinate $\Psi(\mathbf{k}^{*}, \mathbf{r}^{*})$ as $C(k^{*}) = \int S(r^{*})\ |\Psi(\mathbf{k}^{*}, \mathbf{r}^{*})|^{2} d^{3}r^{*}$. Since $\Psi(\mathbf{k}^{*}, \mathbf{r}^{*})$ reflects the interaction between the two particles, the correlation function can be calculated assuming the interaction once the source function is determined from a measured correlation function of two hadrons with a known interaction such as proton-proton. Thus, information on the unknown interaction can be derived. This method called "femtoscopy" has been applied to various hadron-hadron pairs in ALICE, STAR, HADES and others. It has played significant roles in recent studies of baryon-baryon interactions. In particular, this method is powerful for low-momentum s-wave YN interactions that is difficult for scattering experiments. In addition, it is the only method to study YY interactions in the free space because YY scattering experiments are impossible.

In the series of HYP conferences, femtoscopy results on YN and YY interactions were first presented in the previous HYP2018; Λp, $\Lambda\Lambda$ and $\Xi^{-}p$ correlation data were presented from ALICE. Then, ALICE reported $\Omega^{-}p$ and Ξ^{-}-p correlation results [20], which indicate attractive $\Omega^{-}p$ and Ξ^{-}-p forces consistent with the lattice calculations by the HAL QCD group. The $\Omega^{-}p$ channel is quite interesting because HAL QCD predicts a $\Omega^{-}p$ bound state [21]. ALICE also reported a surprisingly precise ΛN correlation function with a clear ΛN-ΣN cusp structure, providing low momentum ΛN interaction data of unprecedented quality contributing to development of the chiral EFT YN interaction [22]. On the other hand, STAR reported $\Xi\Xi$ correlation data for the first time, as well as $p\Xi^-$ and $p\Omega^-$ data [23].

The femtoscopy method has been established as a powerful tool for investigating of baryon-baryon interaction through comparison with the correlation functions calculated with theoretical interactions from the lattice QCD and the chiral effective field theory. In near future, more data with much higher statistics and varieties of the baryon-baryon pair will be available. In order to analyze high quality data, efforts are being made to estimate various effects such as the feed-down effects from other channels and the source size effects, as well as to take into account the coupled-channel effects. In ALICE the femtoscopy method is being extended to nuclear systems such as the *p-d* system, but the measured *pd* correlation is found to be very different from the one expected from the *pd* interaction. Effects of the three-body force and the deuteron formation mechanism are investigated [24].

4.3 ΛNN three-body force and ΛN interaction in neutron stars

The observation of massive neutron stars with twice the solar mass gave a great impact to nuclear physicists, since hyperon appearance expected in the core of neutron stars cannot support such massive neutron stars. One of the scenarios to solve this "hyperon puzzle" is to clarify possible repulsive nature of the density dependence of the ΛN interaction, which is described by the ΛNN three-body force.

In the conference, several theoretical talks on Equation-Of-State (EOS) and the topical session on ΛNN three-body force were given. The topical session mainly discussed theoretical approaches to this problem, but from an experimental point of view, a femtoscopy approach by ALICE to extract the ΛNN force effect from the three-body correlation was presented [25]. To see the effect, more data with a larger statistics by two orders of magnitude is necessary, but is possible with coming RUN3 data.

At J-PARC, new experiments are proposed to study ΛNN three-body force through high precision Λ hypernuclear spectroscopy via the (π^+, K^+) reaction [12] combined with high quality Λp scattering experiments [18], as one of the main program in the J-PARC Hadron Facility extension project [26, 27]. It is noted that Ohnish pointed out a possibility to study ΛN interaction in high density matter via directed flow of Λ hyperons in high energy nuclear collision experiments [28].

In order to investigate ΛN interaction in neutron stars, the Λ binding energy in neutron-rich nuclear matter should be also measured because the ΛNN $(T{=}1)$ interaction which governs the neutron star EOS can be very different from the ΛNN $(T{=}0)$ interaction studied with ordinary (isospin~0) target nuclei. In JLab, a high-resolution $(e, e'K^+)$ Λ hypernuclear spectroscopy experiment on ^{40}Ca and ^{48}Ca targets (E12-15-008) is under preparation [12].

5 Kaonic systems and $\bar{K}N$ interaction

From the strongly-attractive K^-p interaction derived from K^-p atomic and low-energy scattering data, the $\Lambda(1405)$ resonance was interpreted as a $\bar{K}N$ bound state and possible existence of $\bar{K}$-nucleus quasibound states was conjectured more than two decades ago. Since then the $\bar{K}N$ interaction has attracted great attention of hadron and nuclear physicists. Various updated data on kaonic nuclei, $\bar{K}N$ femtoscopy, $\Lambda(1405)$, *etc.*, have been reported as summarized by Doce [29], and the conjecture has been confirmed and accepted through great efforts by theorists.

5.1 Kaonic nuclei

Until recently, no clear experimental evidence was given for the existence of a $\bar{K}$-nucleus quasibound state, although some experiments reported positive suggestions. The J-PARC E15 experiment recently observed a peak located 42 MeV below the K^-pp threshold in the Λp invariant mass spectrum obtained in the K^-+^{3}He $\rightarrow \Lambda pn$ reaction [30]. Since the peak position does not depend on the momentum transfer to the Λp system and the quasi-free K^- absorption process is also observed above the threshold, the peak is reasonably interpreted as a K^-pp bound state. Interestingly, a similar peak was also reported in the Λd invariant mass in the ^{4}He($K^-, \Lambda p$)n reaction [31]. Further studies are planned with a larger cylindrical spectrometer in order to assign its spin-parity and to create heavier kaonic nucleus systems.

5.2 Λ(1405)

Since the mass and the parity (−) of Λ(1405) cannot be explained by orbital excitation of quarks and the mass is close to the K^-p threshold, Λ(1405) was conjectured to have a K^-p molecular structure. This assumption has been confirmed not only by lattice QCD calculations but also by the $\bar{K}N$ amplitude analyzed with the K^-p atomic and low-energy scattering data using the chiral unitary model with the $\bar{K}N$-$\Sigma\pi$ coupled channel. The calculation predicted two-pole structure at 1380 and 1405 MeV [32], which has been supported by several experimental data for $\pi\Sigma$ mass spectra. The Glue X collaboration at JLab Hall D reported a Λ(1405) line shape recently measured via the $\Sigma^0\pi^0$ decay channel. It is well fitted with two Flatte functions at ∼1387 and ∼1409 MeV [33], clearly indicating the two-pole structure.

5.3 Kaonic atoms and low energy $\bar{K}N$ interaction

Although X rays from kaonic atoms have been measured for various elements including the kaonic hydrogen (K^-p), the kaonic deuterium (K^--d) X ray has not been observed yet in spite of its significance in separating the $\bar{K}N$ T=0 and 1 interactions. The SIDDHARTA-2 experiment at DAΦNE and the J-PARC E57 will soon challenge the first observation with silicon drift detectors (SDD) [35]. On the other hand, the J-PARC E62 experiment successfully employed Transition Edge Sensor (TES) with an excellent resolution of ∼30 times better under a high rate beam background. This experiment determined energy shifts of the 2p states in K^--^{3}He and K^--^{4}He atoms with ∼10 times smaller error bars than before [35].

The low-energy K^--nucleus interaction has been also studied by the AMADEUS experiment at DAΦNE, studying the K^- absorption on two, three and four nucleons, as well as $K^-p \rightarrow \Sigma^0/\Lambda\, \pi^0$ cross sections for p_{K^-}∼100 MeV/c [36].

5.4 $\bar{K}N$ interaction from femtoscopy

The femtoscopy technique was also applied to the $\bar{K}N$ interaction. The ALICE collaboration reported the K^-p (and K^+p) correlation [37]. The measured K^-p correlation function from the pp collision clearly exhibits cusp structure at the $K^-p \rightarrow \bar{K}^0 n$ and $K^-p \rightarrow \Lambda$(1520) thresholds. It was compared with the correlation function calculated by taking into account the K^-p-$\Sigma\pi$-$\Lambda\pi$ coupled-channel effects, together with the threshold difference of different charge states such as K^-p-$\bar{K}^0n$ [38]. The data was well reproduced by the predicted curve with a significant coupling to the $\pi\Sigma$ channel. It is noted that the measured correlation function for a large source size in the Pb-Pp collision shows weaker cusp structure, and actually the calculated correlation function for a large source size is found to be less sensitive to the $\pi\Sigma$ coupling. In this way, the femtoscopy method is useful to approach the K^-p amplitude below the threshold coupled to the $\pi\Sigma$ channel.

6 Other topics with strange and heavy flavor hadrons

6.1 Other hadron-hadron interactions

The femtoscopy analysis was also performed for various channels.

Hadron-hadron correlation data including D mesons were presented for the first time by the ALICE collaboration [22]. From the π^+D^- and π^+D^+ data, the scattering lengths for the isospin 3/2 and 1/2 channels were derived and compared with lattice calculations. In addition, pD^- correlation data was also reported. Since recently-observed several exotic hadrons with charm have masses close to the threshold going to two hadrons, they are considered to be candidates of hadron-hadron molecules. The femtoscopy studies with charm will clarify the interaction between the two hadrons and reveal the nature of those exotic hadrons.

On the other hand, the STAR collaboration reported $K_s^0K_s^0$ and $K_s^0K^+$ correlation data [39]. They are reproduced well by calculations with the strong final state interaction through the $f_0(980)$ and $a_0(980)$ scalar resonances. In this way, femtoscopy could be useful in clarifying the structure of such resonances, for example, whether $f_0(980)$ and $a_0(980)$ are $qq\bar{q}\bar{q}$ states or $K\bar{K}$ molecules.

6.2 Hadron polarization in heavy ion collisions

Hyperons are good probes for investigating "global polarization" of particles in hot/dense matter created by high energy nuclear collisions because of the self-analyzing property of hyperon's weak decay. The STAR collaboration discovered a global polarization of Λ hyperons in noncentral nuclear collisions at $\sqrt{s_{NN}}$ = 7.7–62.4 GeV [40], indicating a creation of strongly vortical fluid of quark gluon plasma. Experimental studies have been made for lower collision energies down to $\sqrt{s_{NN}}$ = 7.7 GeV by STAR in Beam Energy Scan [41] and down to $\sqrt{s_{NN}}$ = 2.4 GeV by HADES [42]. The results indicates increasing trend of the polarization to lower energies. In addition, STAR also observed a surprisingly large global spin alignment of ϕ meson at low energies ($\sqrt{s_{NN}} < 62$ GeV) [43].

6.3 Exotic hadrons with heavy flavors

Studies of exotic hadrons (tetraquarks and pentaquarks) with heavy flavors have been actively conducted. In the conference, recently-observed exotic hadrons with charm and strangeness are reviewed [44]. The exotic mesons with open-charm and strangeness, $D^*_{s0}(2317)$ and $D_{s1}(2460)$, are well interpreted as DK and D^*K molecules, respectively. Recently, LHCb reported one or more new exotic resonances, $X(2900)$, decaying to D^-K^+ at the mass close to the $D^*\bar{K}^*$ threshold, which suggests a universal feature of the $\bar{K}$ and $\bar{K}^*$ bound states. In addition, at the mass close to the $\bar{D}^*_sD + \bar{D}_sD^*$ threshold, BESII reported $Z_{cs}(3985)$ in the $e^+e^- \rightarrow K^+X$ reaction, and LHCb reported $Z_{cs}(4000)$ decaying to $J/\psi K^+$. LHCb also reported a hidden charm pentaquark with strangeness, P_{cs}, in the $J/\psi\Lambda$ mass spectrum in the $\Xi_b^0 \rightarrow J/\psi\Lambda K^-$ decay. It is a strange analog of the original pentaquark, P_c, observed in $J/\psi p$ mass in the $\Lambda_b^0 \rightarrow J/\psi pK^-$ decay.

Recent results from Belle data were also reported [45]. A peak was observed in the pK^- mass spectrum at the $\Lambda\eta$ threshold, and is well explained as a threshold cusp rather than a new resonance. It may imply that some of the exotic hadrons observed at thresholds are threshold cusps rather than molecular states. From Belle data, $\Xi_c(2970)$ was assigned to $1/2^+$. It is noted that this state, located ~500 MeV above the Ξ_c ground state, is possibly an analog of the Roper resonance $N(1440)$ with $1/2^+$. It may give a hint to elucidate the Roper resonance that has not been understood yet.

7 Future Facilities

In the conference, various results on hypernuclei and strange (and heavy flavored) hadrons were reported based on recent experiments performed at a variety of facilities in the world, JLab (Hall A, Hall B (CLAS), Hall D (Glue-X)), J-PARC (K1.8, K1.8BR, High-p), GSI/FAIR (HADES, HypHI, WASA-FRS), DAΦNE (SHIDDHARTA, AMADEUS), LHC (ALICE, LHC-b), RHIC (STAR), (Super)KEKB (Belle/Belle II), and BEPCII (BESIII). Their experimental prospects were also reported in the conference. In particular, STAR is collecting lower energy data in Beam Energy Scan, which enables abundant hypernuclear production. ALICE will accumulate much larger statistics data by two orders of magnitude in the coming RUN 3, which will be used for further femtoscopy studies. Glue-X at JLab Hall D is studying hyperon photoproduction with higher energy photon beams than before [34]. Belle2 at SuperKEKB will acquire 50 times more data than Belle [45]. In addition, the following future plans of J-PARC facilities were also presented.

7.1 J-PARC Hadron Facility extension

The J-PARC Hadron Experimental Facility has played significant roles in the recent progress of nuclear and hadron physics with strangeness. In order to enhance the activity, a project is proposed to extend the area of the facility building almost twice and construct a new production target and several new secondary beam lines [27]. The main motivation of the HIHR (High Intensity High Resolution) beam line and the K1.1 beam line is to investigate YNN three-body force via high precision hypernuclear spectroscopy and hyperon-nucleon scattering experiments [26]. The π20 and K10 beam lines will deliver high momentum pions and kaons for spectroscopic studies of charm baryons and multi-strange baryons, respectively.

7.2 J-PARC Heavy Ion project

A further J-PARC project of accelerating heavy ions (J-PARC HI project) is also proposed [46]. In this project, heavy ions are accelerated by a newly-constructed superconducting linac and a booster ring, and then injected to and accelerated by the RCS ring and the Main Ring of J-PARC. Heavy ions can be accelerated up to ~11 GeV/A with the world highest intensity. It will be used to produce dense nuclear matter, and the highest beam intensity will help to detect deconfined quark matter at high density via fluctuation of the particle yields. This project also aims at production of exotic' (proton/neutron rich and multi-strange) hypernuclei and exotic hadrons, as well as femtoscopy studies for hadron-hadron interactions.

8 Concluding remark

At the end, the author dared to choose the highlights of the experimental results in HYP2022.
(1) All the femtoscopy results. This new technique, being applicable to variety of hadron-hadron channels, has clearly changed the game.
(2) High statistics ΣN and ΛN scattering results at J-PARC and JLab. After half a century, the long-awaited significant update of YN scattering data has been achieved.
(3) Ξ hypernuclei in emulsion ($^{15}_{\Xi}$C) and kaonic nuclei ($K^- pp$ and $K^- ppn$) at J-PARC. Both confirmed their existence and determined their binding energies (although further studies are necessary).

All the other experimental results and plans reported in the conference were also valuable and encouraging. Considering theoretical progress as well, the author is looking forward to the next HYP conference with optimistic expectations.

https://doi.org/10.1051/epjconf/202227112001

In HYP2022, the participants enjoyed face-to-face presentations and discussions after difficult years of the Corona disaster. The author appreciates the organizers' decision of postponement of the conference for one year to avoid a full online meeting. The wonderful banquet as well as the fantastic concert and the beautiful city tour also delighted the participants. The author thanks the organizers for their great efforts to realize this memorable event. The HYP2022 conference was closed after the announcement by the conference chair, Jiří Mareš, that the next conference HYP2025 will be held in Japan hosted by S. N. Nakamura.

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