EPJ Web of Conferences **271**, 11002 (2022) https://doi.org/10.1051/epjconf/202227111002
HYP2022

Strangeness physics programs by S-2S at J-PARC

Toshiyuki Gogami[1,*], *Patrick* Achenbach[2], *Jung Keun* Ahn[3], *Darko* Androić[4], *Kanae* Aoki[5], *Arshak* Asaturyan[6], *Elena* Botta[7], *Masroor. H.* Bukhari[8], *Alexandre* Camsonne[9], *Silviu. C.* Covrig[9], *Kengo* Ebata[1,10], *Hiroyuki* Ekawa[11], *Petr* Evtoukhovitch[12], *Alessandro* Feliciello[7], *Hiroyuki* Fujioka[13], *Manami* Fujita[10], *Franco* Garibaldi[14], *Takeshi. K.* Harada[1,10], *Shoichi* Hasegawa[10], *Tomoyuki* Hasegawa[15], *Shuhei. H.* Hayakawa[16], *Erina* Hirose[5], *Ryotaro* Honda[5], *Kenji* Hosomi[10], *Yudai* Ichikawa[10], *Kenichi* Imai[10], *Tatsuhiro* Ishige[16], *Wooseung* Jung[3], *Kento* Kamada[16], *Shunsuke* Kanatsuki[1], *Seigo* Kato[17], *Shinhyung. H.* Kim[10], *Takumi* Kobori[13], *Simonetta* Marcello[7], *Pete* Markowitz[18], *Koji* Miwa[16], *Arthur* Mkrtchyan[19], *Hamlet* Mkrtchyan[19], *Manabu* Moritsu[20], *Tomofumi* Nagae[1], *Sho* Nagao[21], *Manami* Nakagawa[11], *Satoshi. N.* Nakamura[21], *Takuya* Nanamura[1,10], *Megumi* Naruki[1], *Ryosuke* Negishi[13], *Kazuki* Okuyama[16], *Fumiya* Oura[16], *Bishnu* Pandey[22], *Josef* Pochodzalla[2], *Atsushi* Sakaguchi[23], *Tamao* Sakao[16], *Hiroyuki* Sako[10], *Chhanda* Samanta[22], *Susumu* Sato[10], *Mitra. H.* Shabestari[24], *Albert* Shahinyan[19], *Kotaro* Shirotori[25], *Simon* Širca[26], *C.* Son[16], *Hitoshi* Sugimura[5], *Hitoshi* Takahashi[5], *Shuji* Takahashi[1], *Tomonori* Takahashi[25], *Toshiyuki* Takahashi[5], *Hirokazu* Tamura[16], *Kiyoshi* Tanida[10], *Atsushi* Tokiyasu[27], *Zviadi* Tsamalaidze[12,28], *Makoto* Uchida[13], *Mifuyu* Ukai[5], *Chiaki* Une[13], *Guido. M.* Urciuoli[14], and *Takeshi. O.* Yamamoto[10] for the S-2S Collaboration

[1]Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502 Japan
[2]Institute for Nuclear Physics, Johannes Gutenberg-University, D-55099 Mainz, Germany
[3]Department of Physics, Korea University, Seoul 136-713, Korea
[4]Department of Physics & Department of Applied Physics, University of Zagreb, HR-10000 Zagreb, Croatia
[5]Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki 305-0801, Japan
[6]University of North Carolina Wilmington (UNCW), NC 28403, USA
[7]Istituto Nazionale di Fisica Nucleare-Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy
[8]Jazan University, Jazan 45142, Saudi Arabia
[9]Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA
[10]ASRC, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan
[11]RIKEN, Wako, Saitama 351-0198, Japan
[12]Joint Institute for Nuclear Research, Dubna, Moscow Region 141980, Russia
[13]Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan
[14]INFN, Sezione di Roma, 00185, Rome, Italy
[15]School of Allied Health Sciences, Kitasato University, Sagamihara, Kanagawa 252-0373, Japan
[16]Department of Physics, Tohoku University, Sendai, Miyagi 980-8578, Japan
[17]Department of Physics, Yamagata University, Yamagata, Yamagata 990-8560, Japan
[18]Department of Physics, Florida International University, Miami, Florida 27411, USA
[19]A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute), Yerevan 0036, Armenia
[20]Department of Physics, Kyushu University, Fukuoka, Fukuoka 819-0395, Japan
[21]Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan
[22]Department of Physics & Astronomy, Virginia Military Institute, Lexington, Virginia 24450, USA
[23]Department of Physics, Osaka University, Osaka 560-0043, Japan

[*]e-mail: gogami.toshiyuki.4a@kyoto-u.ac.jp

 https://doi.org/10.1051/epjconf/202227111002

[24]Department of Physics, University of West Florida, FL 32514, USA
[25]Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
[26]Faculty of Mathematics and Physics, University of Ljubljana, 1000 Ljubljana, Slovenia
[27]Research Center for Electron Photon Science, Tohoku University, Sendai, Miyagi 982-0826, Japan
[28]Georgian Technical University (GTU), Tbilisi, Georgia

Abstract. In the K1.8 beam-line at Hadron Experimental Facility of J-PARC, a new magnetic spectrometer S-2S is being installed. S-2S was designed to achieve a high momentum resolution of $\Delta p/p = 6 \times 10^{-4}$ in FWHM. Several strangeness-physics programs which require the high resolution will be realized by S-2S. The present article introduces J-PARC E70 (missing-mass spectroscopy of $^{12}_{\Xi}$Be) and E94 (missing-mass spectroscopy of $^{7}_{\Lambda}$Li, $^{10}_{\Lambda}$B, and $^{12}_{\Lambda}$C) experiments.

1 Introduction

Hypernuclear spectroscopy is a significant tool to study the baryon-baryon (BB) interaction with strangeness degrees of freedom (S). The interaction between Λ and nucleon (ΛN), which is the $S = -1$ system, has been being explored by Λ hypernuclear spectroscopy [1–3] and ΛN-scattering experiments [4–6]. Despite the $S = -1$ hypernuclei have been investigated for about 70 years since the first hypernuclear event was reported in 1953 [7], the number of observed hypernuclear species and data qualities are still limited. Moreover, the BB interaction for $S = -2$ baryons is quite unknown because experimental data of such as double-Λ or Ξ hypernuclei are much fewer than those for the $S = -1$ system. Nuclear emulsion experiments that found potential events of the $S = -2$ hypernuclei [8–13] allow us to consider the $\Lambda\Lambda$ and ΞN interactions are weakly attractive. In addition, recent data of femtoscopy by the ALICE Collaboration show similar attractive behaviors for the ΞN and $\Lambda\Lambda$ interactions [14–17]. These successful findings lead to a prediction of the existence of bound hypernuclei with $S = -2$, and they strongly motivate us to go forward to a systematic investigation of Ξ (double-Λ) hypernuclei to study the ΞN ($\Lambda\Lambda$) interaction.

At the beginning of 2022, an installation of a new magnetic spectrometer, Strangeness -2 Spectrometer (S-2S), started at the K1.8 beam-line at Hadron Experimental Facility of J-PARC [18, 19]. S-2S was designed for a missing-mass spectroscopy of Ξ hypernuclei with the world's best energy resolution of 2 MeV in the full width at half maximum (FWHM). One of the important features of S-2S is the high momentum resolution of 6×10^{-4} in FWHM, maintaining a reasonable solid-angle acceptance of about 55 msr at the central momentum. The installation of S-2S magnets and detectors is planned to be completed by the end of 2022. The first S-2S commissioning by using the beam is going to be carried out in the beginning of 2023. A new era to study the $S = -2$ hypernuclei with the high-precision reaction-spectroscopy is about to be begun. There are several strangeness-physics programs with S-2S, which are labeled E70 (missing-mass spectroscopy of $^{12}_{\Xi}$Be) [20], E75 [missing-mass spectroscopy of $^{7}_{\Xi}$H (phase-1 experiment); decay-pion spectroscopy of $^{5}_{\Lambda\Lambda}$H (phase-2 experiment)] [21, 22], E90 (ΣN-cusp measurement) [23], E94 (missing-mass spectroscopy of $^{7}_{\Lambda}$Li, $^{10}_{\Lambda}$B and $^{12}_{\Lambda}$C) [24] and E96 (X-ray measurement from ^{12}C-Ξ^- atom) [25] so far. Other experimental ideas which we are examining can be found in Ref. [26]. In the present article, the E70 and E94 experiments are described since some details of the others may be shown elsewhere in the same volume of the present journal.

2 Ξ hypernuclear study in J-PARC E70

2.1 Experimental setup

The S-2S spectrometer consists of two quadrupole (Q1 and Q2) magnets, one dipole (D) magnet, and particle detectors. The magnetic flux density of the D magnet is 1.5 T at the maximum coil current of 2500 A, and it bends charged particles at about 1.37 GeV/c by 70°. The particle detectors are composed of plastic-scintillation counters for a data-taking trigger, five layers of drift chambers (SDC1–5) for a particle tracking, and two types of Cherenkov counters (radiation media of aerogel and water) for a particle identification [27, 28]. Figure 1 shows a picture of S-2S as of the end of June 2022. The back face of SDC5 and a common frame which holds SDC3–5 are seen in the downstream of the D magnet in the picture. The other detectors are now being installed. A K^--meson beam transported by the K1.8 beam-

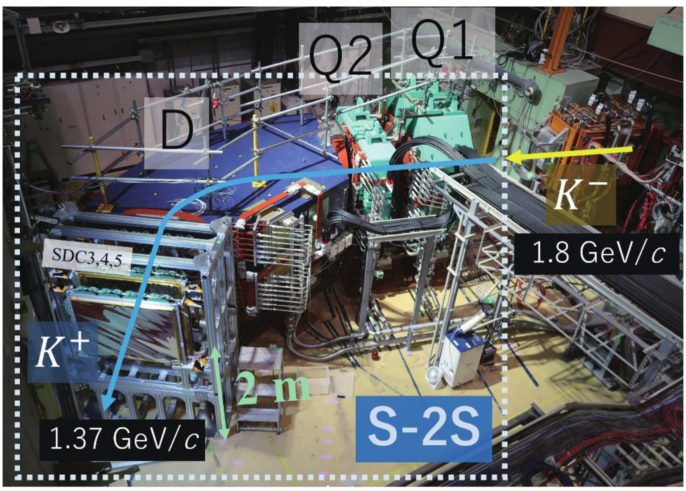

Figure 1. A photograph of S-2S which is installed in the K1.8 beam-line at Hadron Experimental Facility of J-PARC as of the end of June, 2022. SDC3–5 are drift chambers for the particle tracking, and the back face of SDC5 is seen in the photograph. Plastic scintillation counters, aerogel-Cherenkov counters, and water-Cherenkov counters are installed in the downstream of SDC5 in this order.

line spectrometer is impinged on an experimental target to produce Ξ hypernuclei through the reaction of (K^-, K^+) at $p_{K^-} = 1.8$ GeV/c. It is worth noting that the reaction rate for the $p(K^-, K^+)\Xi^-$ reaction was found to be the maximum at $p_{K^-} \simeq 1.8$ GeV/c within the range of $1.5 \leq p_{K^-} \leq 1.9$ GeV/c [29] in the previous experiment (J-PARC E05) [28, 30]. The generated K^+ is detected and momentum-analyzed by S-2S. The central momentum of S-2S is set to 1.37 GeV/c to cover the kinematics for the $p(K^-, K^+)\Xi^-$ reaction, which is used for an energy calibration, as well as the $^{12}\mathrm{C}(K^-, K^+)^{12}_{\Xi}\mathrm{Be}$ reaction. The experimental target (AFT: active fiber target) is composed of scintillation fibers with a core of polystyrene (C : H = 1 : 1). Therefore, data of the energy calibration and Ξ hypernuclei are taken simultaneously. AFT measures the energy loss of charged particles event by event. The energy-loss information in AFT is used when the missing-mass is reconstructed to suppress the mass-resolution deterioration due to the energy straggling. The goal of missing-mass resolution is about 2 MeV/c^2 in FWHM, and is expected to be realized by applying the event-by-event correction for the energy loss.

2.2 Expected results

In the J-PARC E70 experiment, the expected number of events in the bound region is about 100 counts for the $^{12}\mathrm{C}(K^-, K^+)^{12}_{\Xi}\mathrm{Be}$ reaction. Assumptions for the yield estimation are shown below. The beam intensity is assumed to be 8×10^5 K^-'s per spill with the spill cycle of 4.2 seconds. It is noted that, in a beam test in 2021, the ratio of K^- to π^- was achieved to be 1.67 and 0.38 at the K^--beam intensity of 6.5×10^5 and 8.6×10^5 per spill, respectively. A typical path length from the target to the end of the S-2S particle detector (water-Cherenkov counter) is 8 m, and thus the fraction of survived K^+'s is 0.46. The particle-detection efficiency which takes into account various efficiencies of such as the detectors, data acquisition system, and data analysis is assumed to be 0.5. The 9-g/cm^2 thick AFT, which is mostly composed of polystyrene (CH), is exposed to the beam for 480 hours. The assumed differential cross section is 60 nb/sr for our angular acceptance of $0° \leq \theta_{K^+} \leq 10°$. Here, the cross-section assumption is based on a result from the past experiment at BNL [31] in which the mass resolution was 14 MeV$/c^2$ (FWHM).

Figure. 2 shows expected binding-energy (B_Ξ) spectra for the $^{12}\mathrm{C}(K^-, K^+)^{12}_{\Xi}\mathrm{Be}$ reaction by a simple Monte-Carlo simulation. The assumed energy resolutions for the left and right

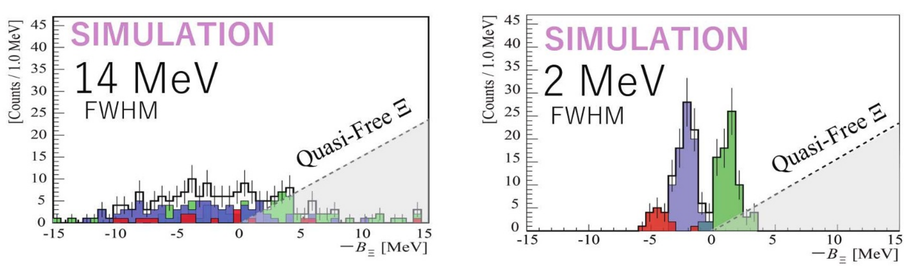

Figure 2. Expected spectra of the Ξ binding energy taken with the negative sign ($-B_\Xi$) for the reaction of $^{12}\mathrm{C}(K^-, K^+)^{12}_{\Lambda}\mathrm{Be}$. Assumed energy resolutions in the left and right panels are 14 and 2 MeV in FWHM, respectively. J-PARC E70 aims to achieve the 2-MeV resolution in FWHM (right panel). The peak positions and relative peak strengths for the assumed three states ($J^\pi = 1^-_1$, 1^-_2 and 1^-_3), which are shown in different colors, are taken from a prediction by DWIA with the interaction model of ESC08a [32].

panels in the figure are 14 and 2 MeV in FWHM, respectively. The left and right panels correspond to the energy resolutions for the cases of the past BNL experiment [31] and J-PARC E70. There are three of assumed states, $J^\pi = 1^-_1$, 1^-_2 and 1^-_3, which are shown in different colors. The energy levels and their relative cross sections are taken from a prediction by DWIA calculation with the interaction model of ESC08a [32]. J-PARC E70 would be able to observe the peak structures separately thanks to the high resolution, and provide significant information of the ΞN interaction.

3 Λ hypernuclear study in J-PARC E94

3.1 Overview

J-PARC E94 aims to establish a high resolution spectroscopy of Λ hypernuclei with the (π^+, K^+) reaction [24]. The highest energy resolution in the missing-mass spectroscopy of Λ hypernuclei with the (π^+, K^+) reaction is about 1.5 MeV in FWHM, which was realized at KEK [33]. On the other hand, the J-PARC E94 aims to achieve 1 MeV (FWHM) or a little better. Such a high resolution is expected to be realized thanks to the high momentum resolution of the new magnetic spectrometer S-2S. A similar or better energy resolution, which is 0.5–1 MeV in FWHM, was already realized by the missing-mass spectroscopy with the $(e, e'K^+)$ reaction at the Thomas Jefferson Lab (JLab) [34–37]. However, the improvement of the energy resolution for the spectroscopy with the (π^+, K^+) reaction gives a large impact to the study of the ΛN interaction because hypernuclear species which can be studied by the (π^+, K^+) and $(e, e'K^+)$ reactions is different. Therefore, complementary investigation of the ΛN interaction through the Λ hypernuclear spectroscopy would be dramatically strengthened.

J-PARC E94 aims to determine the absolute binding energy with the accuracy of $|\Delta B_\Lambda| \simeq$ 100 keV. Such a high accuracy could not be realized in the past (π^+, K^+) experiments because a source of the energy calibration was the ground-state binding energy of $^{12}_{\Lambda}$C [$B^{\rm g.s.}_\Lambda(^{12}_{\Lambda}{\rm C})$]. The measured $B^{\rm g.s.}_\Lambda(^{12}_{\Lambda}{\rm C})$ is known to be $10.76 \pm 0.19 \pm 0.04$ MeV [38]. The error on $B^{\rm g.s.}_\Lambda(^{12}_{\Lambda}{\rm C})$, which is about 200 keV, propagates to the uncertainty of measured Λ binding energies when it is used for the calibration. In addition, it is pointed out that $B^{\rm g.s.}_\Lambda(^{12}_{\Lambda}{\rm C})$ is shifted by about 500–600 keV [39, 40], which could lead to an additional systematic error on the binding-energy measurement. Therefore, J-PARC E94 tries to use different calibration sources, the binding energies of $^{7}_{\Lambda}{\rm Li}(1/2^+, 5/2^+)$. The binding energies of these states were well determined by the emulsion experiment [38] and γ-ray spectroscopy [41, 42] with high statistics. Their energy uncertainties are only about 50 keV. The small uncertainties of the calibration sources allow us to reach the high accuracy of $|\Delta B_\Lambda| \simeq 100$ keV in J-PARC E94. The binding energies of the $1/2^+$ and $5/2^+$ states of $^{7}_{\Lambda}$Li were not be able to be used before because the energy separation between the states is only about 2 MeV and could not be separated with the energy resolutions in the past experiments. The use of $^{7}_{\Lambda}$Li for the calibration purpose is expected to be realized for the first time thanks to the high energy resolution of about 1 MeV (FWHM) in J-PARC E94.

J-PARC E94 aims to prove that the missing-mass spectroscopy with the 1-MeV resolution and the 100-keV accuracy is possible via the (π^+, K^+) reaction by measuring $^{7}_{\Lambda}$Li, $^{10}_{\Lambda}$B, and $^{12}_{\Lambda}$C. The accurate measurement of $^{12}_{\Lambda}$C would clarify the issue of the energy shift of about 500–600 keV in the existing data of $B^{\rm g.s.}_\Lambda(^{12}_{\Lambda}{\rm C})$ [39, 40]. In addition, the accurate data of $^{10}_{\Lambda}$B would lead to better understanding of the charge-symmetry breaking [43, 44] by comparing with its mirror hypernucleus $^{10}_{\Lambda}$Be [39].

3.2 Experimental conditions and status

The experimental setup for the J-PARC E94 is the same as that for J-PARC E70 except for the beam polarity, momentum settings of the spectrometers (both the beam-line spectrometer and S-2S), and experimental targets. The π^+ beam at $p_{\pi^+} = 1.05$ GeV/c is impinged on the experimental target. Target materials of ^{7}Li, ^{10}B, and ^{12}C with the areal density of 1 g/cm^2 are alternately installed to measure $^{7}_{\Lambda}$Li, $^{10}_{\Lambda}$B, and $^{12}_{\Lambda}$C, respectively, by the (π^+, K^+) reaction. The central momentum of S-2S is set to 0.72 GeV/c.

J-PARC E94 was approved to be at the Stage 1 in 2022. We are now allowed to apply to the Stage 2 which is the final status to perform the experiment. A systematic investigation with the high resolution and high accuracy for the other Λ hypernuclei, which may be up to the medium-heavy mass region (A ∼ 50), would be promising by S-2S in the future if J-PARC E94 is successfully completed.

4 Summary

The new magnetic spectrometer S-2S is being installed in the K1.8 beam-line at Hadron Experimental Facility of J-PARC. S-2S was designed to achieve the high momentum resolution of $\Delta p/p = 6 \times 10^{-4}$ (FWHM). Several strangeness-physics programs in which the high resolution measurements are required will be realized by S-2S. In the present article, J-PARC E70 (missing-mass spectroscopy of ${}^{12}_{\Xi}$Be) and E94 (missing-mass spectroscopy of ${}^{7}_{\Lambda}$Li, ${}^{10}_{\Lambda}$B, and ${}^{12}_{\Lambda}$C) experiments are described. The S-2S commissioning with the hadron beam is planned to be performed in the beginning of 2023, followed by the calibration and physics runs of J-PARC E70.

Acknowledgments

We thank J-PARC staff for supporting our experimental programs. This work was supported by JSPS KAKENHI Grant Numbers 17070006, 17070005, 22244025, 23000003, 13J01075, 16H02186, 18H05403, 18H01219. This work was supported by SPIRITS 2020 of Kyoto University.

References

[1] O. Hashimoto and H. Tamura, Prog. Par. Nucl. Phys. **57**, 2, 564–653 (2006)
[2] A. Feliciello and T. Nagae, Rep. Prog. Phys. **78**, 9 (2015)
[3] A. Gal, E. V. Hangerford, and D. J. Millener, Rev. Mod. Phys. **88**, 035004 (2016)
[4] T. H. Groves, Phys. Rev. **129**, 1372 (1963)
[5] G. Alexander et al., Phys. Rev. **173**, 1452 (1968)
[6] J. Rowley et al., Phys. Rev. Lett. **127**, 272303 (2021)
[7] M. Danysz and J. Pniewski, The London, Edinburgh, and Dublin Phil. Mag. Jour. Sci. **44**:350, 345–350 (1953)
[8] H. Takahashi et al., Phys. Rev. Lett. **87**, 212502 (2001)
[9] J. K. Ahn et al., Phys. Rev. C **88**, 014003 (2013)
[10] K. Nakazawa et al., Prog. Theor. Exp. Phys. **2015**, 033D02 (2015)
[11] H. Ekawa et al., Prog. Theor. Exp. Phys. **2019**, 021D02 (2019)
[12] M. Yoshimoto et al., Prog. Theor. Exp. Phys. **2021**, 073D02 (2021)
[13] S. H. Hayakawa et al., Phys. Rev. Lett. **126**, 062501 (2021)
[14] S. Acharya et al. (ALICE Collaboration), Phys. Lett. B **797**,134822 (2019)
[15] S. Acharya et al. (ALICE Collaboration), Phys. Rev. Lett. **123**, 112002 (2019)
[16] S. Acharya et al. (ALICE Collaboration), Nature **588**, 232 (2020)
[17] Y. Kamiya et al., Phys. Rev. C **105**, 014915 (2022)
[18] K. Agari et al., Prog. Theor. Exp. Phys. **2012**, 02B009 (2012)
[19] T. Takahashi et al., Prog. Theor. Exp. Phys. **2012**, 02B010 (2012)
[20] T. Nagae et al., *Proposal for the next E05 run with the S-2S spectrometer*, Proposal to J-PARC, E70 (2018)
[21] H. Fujioka et al., *Decay Pion Spectroscopy* ${}^{5}_{\Lambda\Lambda}H$ *produced by* Ξ*-hypernuclear decay*, Proposal to J-PARC, E75 (2019)
[22] H. Fujioka et al., *Phase-1 of the P75 experiment: Measurement of the formation cross section of* ${}^{7}_{\Xi}H$ *in the* ${}^{7}\mathrm{Li}(K^-, K^+)$ *reaction*, Proposal to J-PARC, E75 Phase-1 (2020)
[23] Y. Ichikawa et al., *High resolution spectroscopy of the* ΣN *cusp by using the* $d(K^-, \pi^-)$ *reaction*, Proposal to J-PARC, E90 (2022)
[24] T. Gogami et al., *New generation* Λ *hypernuclear spectroscopy with the* (π^+, K^+) *reaction by S-2S*, Proposal to J-PARC, E94 (2022)
[25] T. O. Yamamoto et al., *Measurement of X rays from* Ξ^-*C atom with an active fiber target system*, Proposal to J-PARC, E96 (2022)

[26] S-2S workshop 2021, https://kds.kek.jp/event/39644/
[27] T. Gogami et al., Nucl. Instrum. Methods, Phys. Res. Sect. A **817**, 70–84 (2016)
[28] T. Gogami et al., JPS Conf. Proc. **18**, 011031 (2017)
[29] T. Gogami et al., J. Phys.:Conf. Ser. **1643**, 012133 (2020)
[30] T. Nagae et al., AIP Conf. Proc. **2130**, 020015 (2019)
[31] P. Khaustov et al., Phys. Rev. C **61**, 054603 (2000)
[32] T. Motoba and S. Sugimoto, Nucl. Phys. A **835**, 223–230 (2010)
[33] H. Hotchi et al., Phys. Rev. C **64**, 044302 (2001)
[34] S. N. Nakamura et al., Phys. Rev. Lett. **110**, 012502 (2013)
[35] L. Tang et al., Phys. Rev. C **90**, 034320 (2014)
[36] T. Gogami et al., Nucl. Instrum. Methods, Phys. Res. Sect. A **900**, 69–83 (2018)
[37] T. Gogami et al., Phys. Rev. C **103**, L041301 (2021)
[38] D. H. Davis, Nucl. Phys. A **754**, 3c–13c (2005)
[39] T. Gogami et al., Phys. Rev. C **93**, 034314 (2016)
[40] E. Botta et al., Nucl. Phys. A **960**, 165–179 (2017)
[41] K. Tanida et al., Phys. Rev. Lett. **86**, 10 (2001)
[42] M. Ukai et al., Phys. Rev. C **73**, 012501(R) (2006)
[43] E. Hiyama and Y. Yamamoto, Prog. Theor. Phys. **128**, 1, 105–124 (2012)
[44] A. Gal and D. Gazda, J. Phys.:Conf. Ser. **966**, 012006 (2018)